AD-A154 649 MULTIAPERTURE OPTICAL SYSTEM RESEARCH(U) RTS LABS INC GAINESVILLE FL JAN 84 N00014-84-C-0592 1/1

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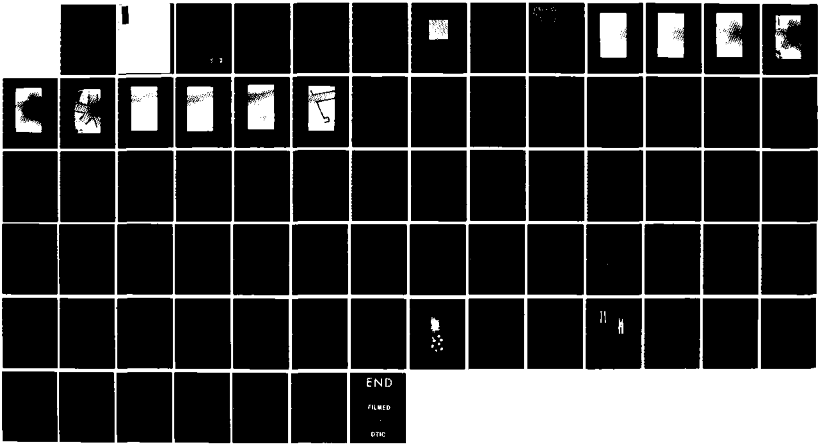

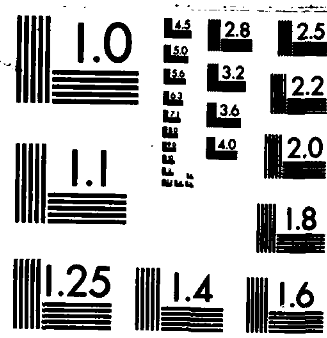

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AD-A154 649

FINAL REPORT

for

Contract Number N00014-84-C-0592

entitled

MULTIAPERTURE OPTICAL SYSTEM RESEARCH

RTS LABORATORIES, INC.
2603 N. W. 74th Place
Gainesville, Florida 32606

January 1984

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I. INTRODUCTION

The principles of multiaperture optics are covered in more detail in Appendix A. Therefore here it will suffice to repeat the basics.

A lens correlates unambiguously one object point with one and only one image point. In the case of multiaperture optics (MAO) one object point may be observed by several eyelets, which in turn may create disks, rings, or even irregularly shaped figures as image elements - corresponding to the one object point. The correlation albeit being non-immaging is unambigous but also multiple, allowing verification by coincidence. The advantages of multiaperture optics are:

~~1.~~ Small size;
~~2.~~ Ruggedness;
~~3.~~ Mass production;
~~4.~~ Large field of view; and
~~5.~~ No focussing required.

It was the object of the effort reported here to explore if such a device could be built and to predict the performance of such a device by computer model.

II. EXPERIMENTAL EFFORT

A. The MAO Camera

The MAO camera developed under the present effort consists of a MAO mask and an optical RAM. Figure 1 shows a schematic of this device. The radius of curvature is 75 mm. All dimensions given in Figure 1 are in millimeters. The MAO mask has a diameter of 13 mm, although only an area of about 2 x 5 mm is used, which is the size of the optical RAM. The diameter of the individual light horns is 100μm. They are in a close packed configuration with a fill factor of 50 percent, meaning the lighthorns are on the average one diameter apart. Figure 2 shows a microscopic phtotograph of a part of the mask. For this particular first try the light horns are cylinders, however, the process of how to manufacture cones is now understood and future masks will have cones rather than cylinders as light horns. The individual cylinders are aligned in a way that their axes all intersect at a point 75 mm from the surface of the mask. The wall of the light horns are not silvered, so that this particular mask depends on total reflection for the off-axis beams. Since these walls consist of black glass, some of the off-axis beams are attenuated while being reflected, which is used as a mechanism to limit the angle of acceptance of each light horn. At low exposure times the off-axis beams

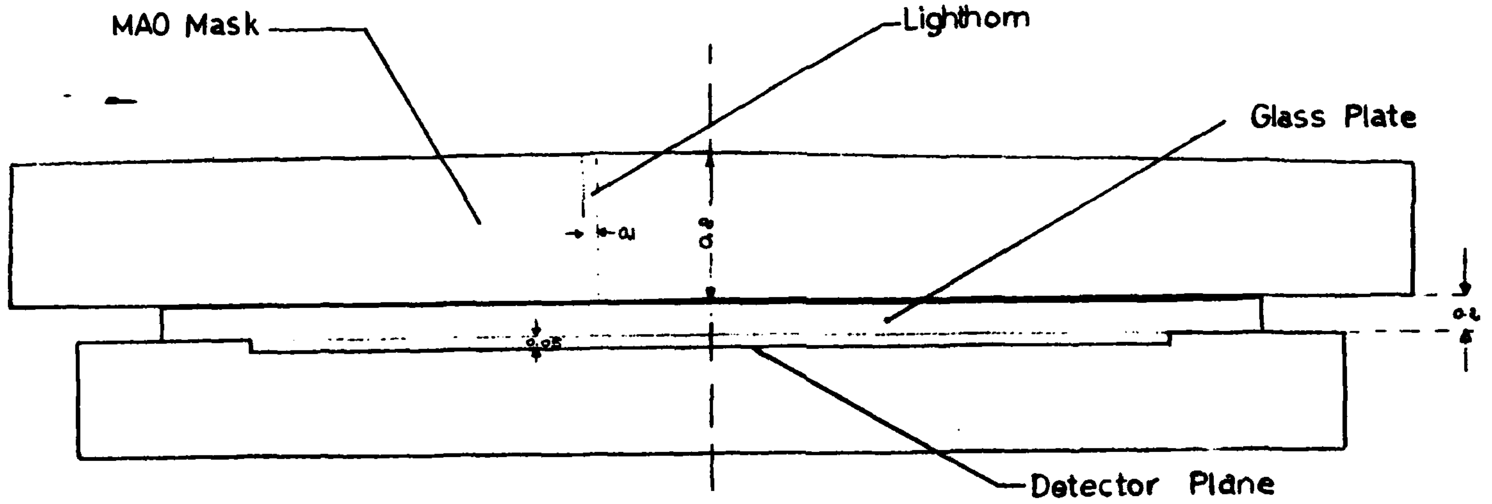
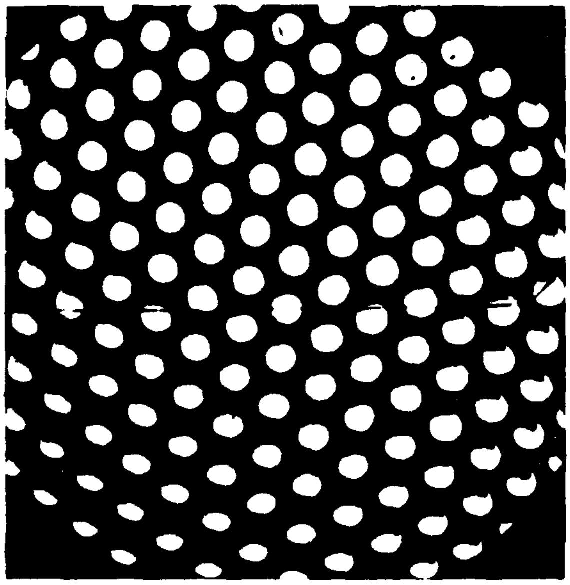


Figure 1.

MAO Camera



5X

Figure 2
Microscope Photograph of MAO Mask

are attenuated enough that they are not registered and therefore the footprint of the light horn is a circle. At longer exposure times the circles get larger and finally grow together as the higher order off-axis beams become registered.

The optical RAM used in the MAO camera is the "IS32A Optic RAM" manufactured by Micron Technology, Inc. It is composed of two arrays of 128 x 256 detectors. The total number of detectors is therefore 65563. Each array is 877 x 4420μm. The two arrays are separated by a dead space 120μm wide. The optical RAM is a random access device, each detector may be uniquely accessed. The image created by the optical RAM is digital, therefore a binary image is obtained. Gray levels may be obtained by multiple scans at different exposure times. The device can be scanned with a clock rate of 4.9 MHz. Exposure times for complete images start at 1 msec. Access times to individual detectors are on the order of 200 nsec.

B. Performance of the MAO Camera

Figure 3 shows the output of the MAO camera when exposed to uniform white light. The fact that the "footprints" in Figure 3 are elipses rather than circles is incidental. It is caused by the printer which allocates different distances for character separation and line separation. Figure 4 shows a series of printouts of a 6 legged cross. The ends of the cross should be square and the corner at the end of each leg should be a 90 degree corner. The fact that it is not has to do with the fact that the light horns are arranged in a hexagonal matrix and the optic RAM has different distances between rows and between individual detectors and columns. On top of this the printer distorts it further. Since the MAO device is not intended as a TV camera but as a digital recognition device these distortions are of no consequence. The device is given a certain shape to recognize and it sees it distorted when "taught," so it will always see it distorted the same way when it tries to recognize the object.

Figure 4 shows the cross for several exposure times, namely 6, 8, 13, 22, 56 millisec. The cross becomes somewhat bigger at larger exposure times. This is caused by the FOV overlap between neighboring eyelets. Off-axis beams which are reflected several times are observed by a row of eyelets, which is really outside the target. These high order beams are only registered at the larger exposure times and thus make the image appear larger. Figure 5 repeats the image of Figure 4 with the outline of the cross drawn in.

Another phenomenon can be seen in Figure 6 which is the image of an airplane at different exposure times (10, 12, 16 msec). Figure 7 shows the airplane drawn

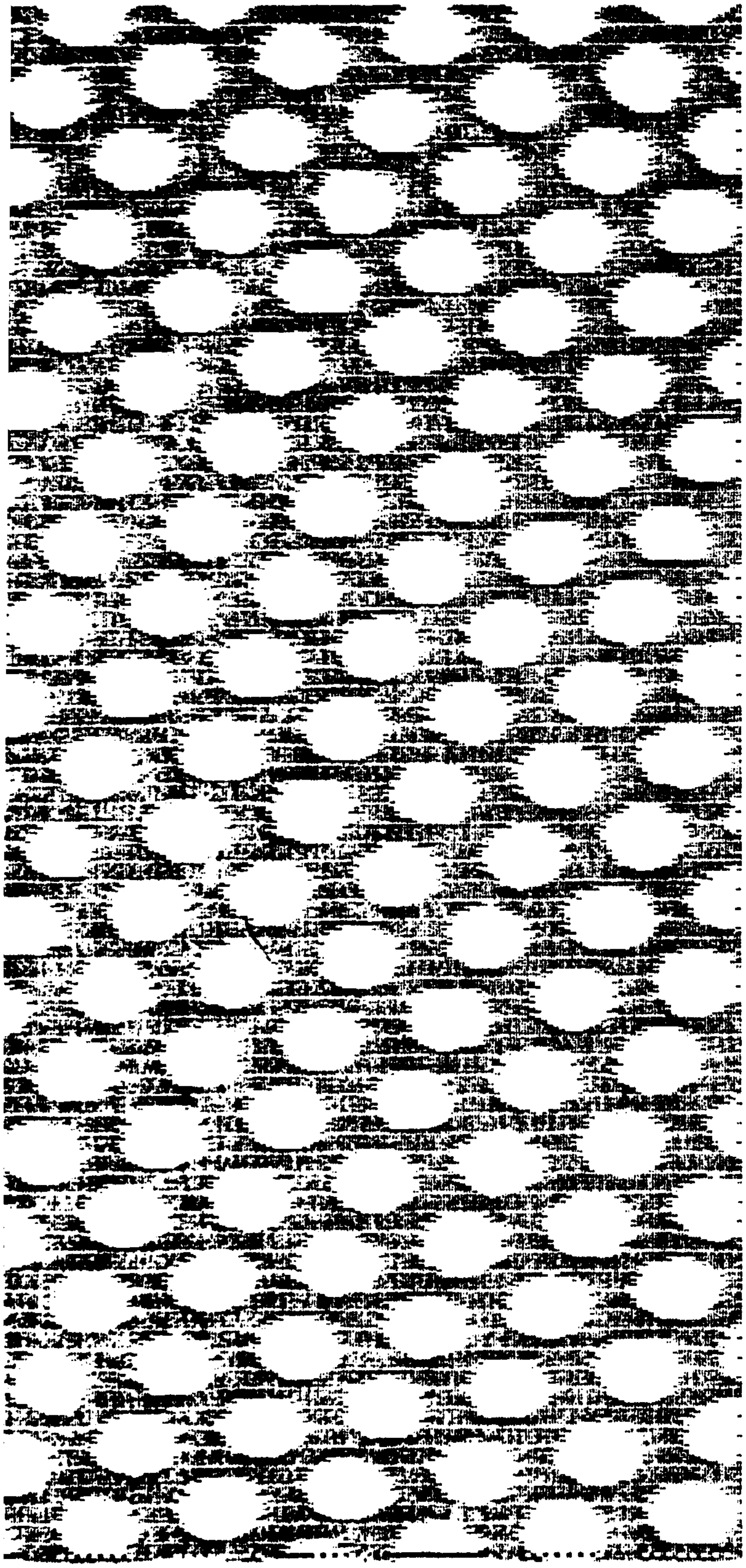


Figure 3

Output of MAO Camera for Uniform Illumination

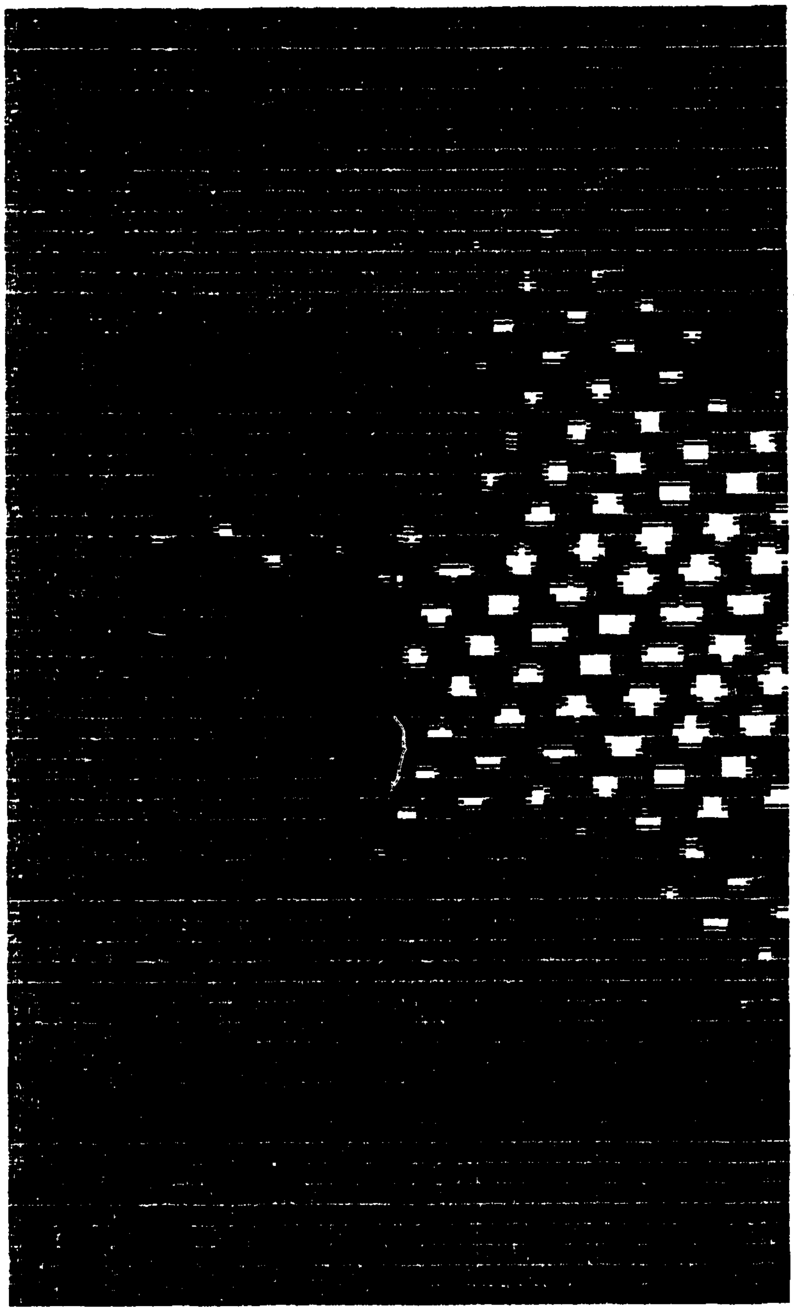


Figure 4a
Six Legged Cross - 6 millisec.

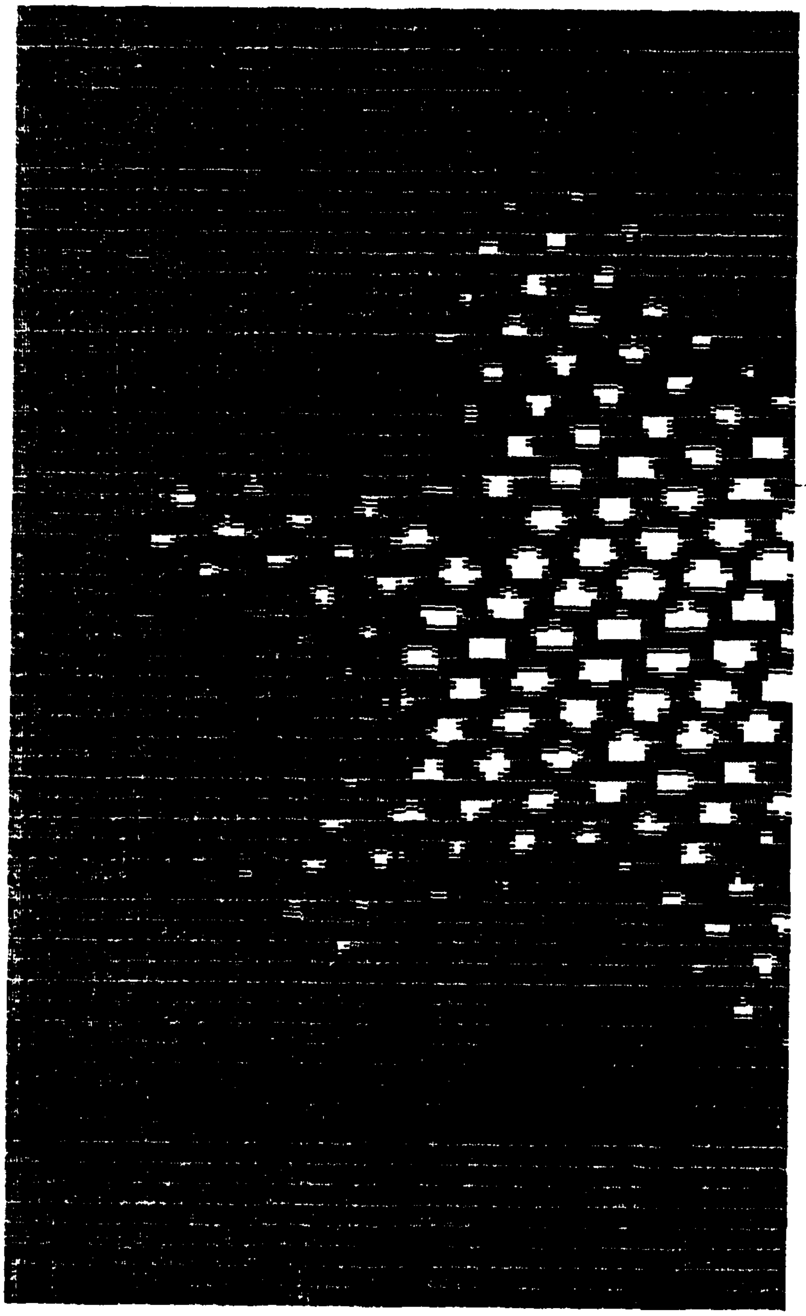


Figure 4b

Six Legged Cross - 8 millisec.

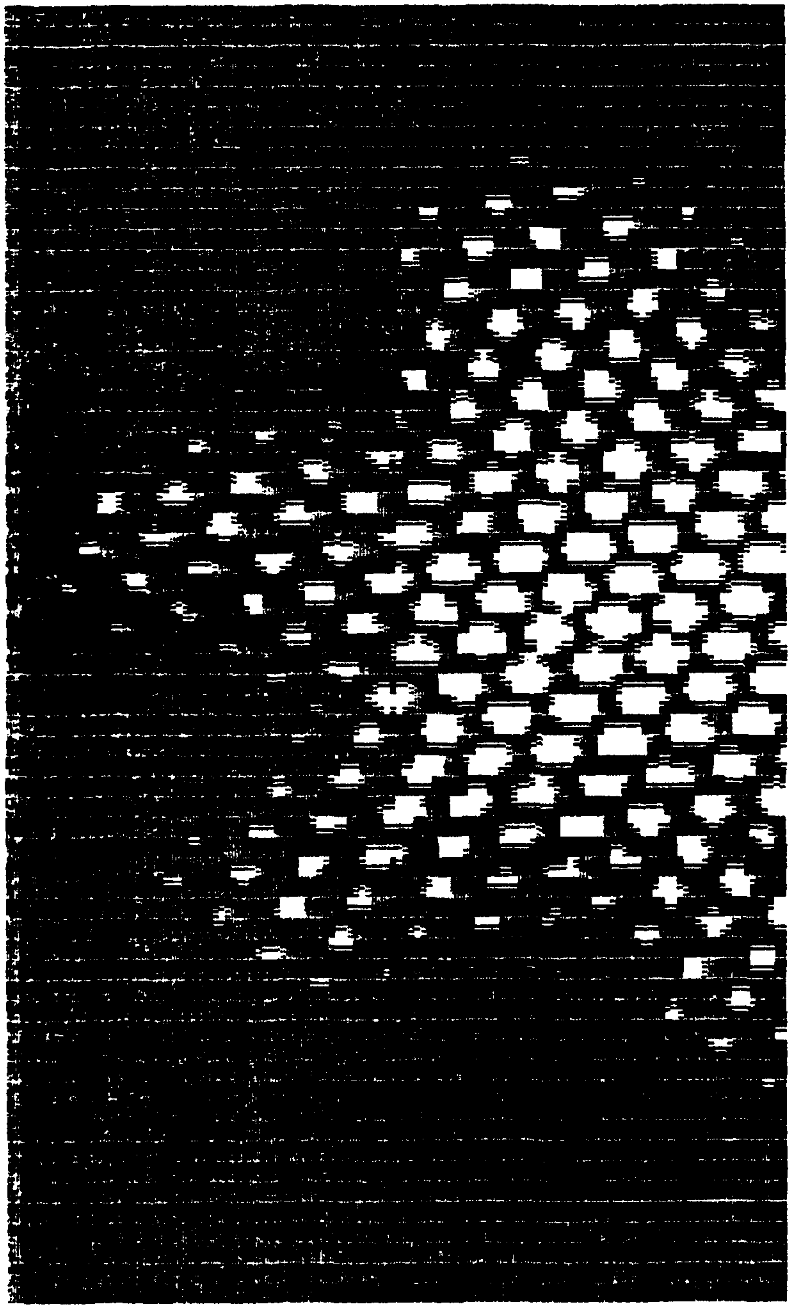


Figure 4c

Six Legged Cross - 13 millisec.

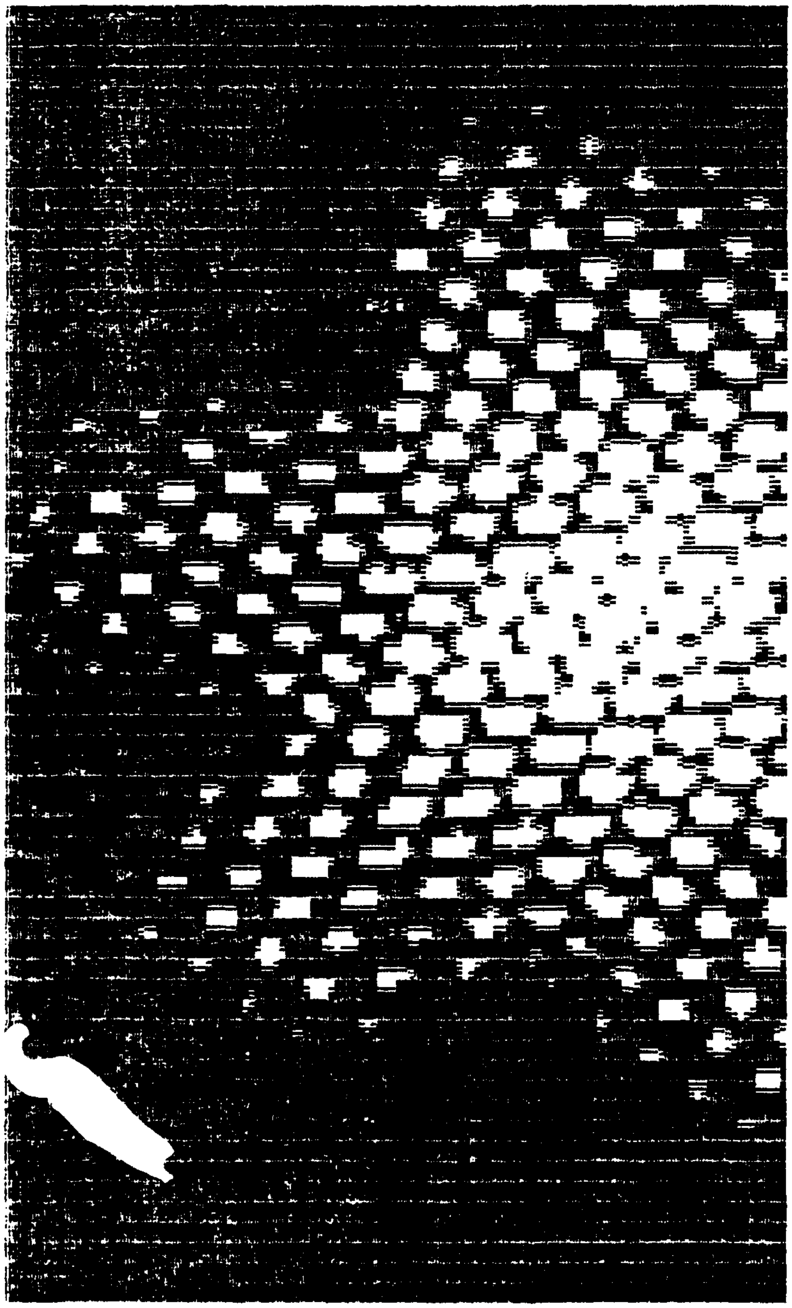


Figure 4d

Six Legged Cross - 22 millisec.

C. Results

The parametric study of the MAO system characteristics centered around the effect of various parametric changes on the signal-to-noise ratios in both zones 1 and 2. The conditions for all other parameters remained fixed as shown in a sample output from the physics code (see Figure 10). The signal-to-noise ratio for zone 1 increases dramatically as the half angle of the light cone increases while the signal-to-noise ratio in zone 2 decreases. This effect occurs because the acceptance angle for each zone increases with cone angle but for zone 2 the exit angle increases at a faster rate and distributes the collected intensity over a larger footprint (see Figure 11 and 12). Figure 13 shows a similar result for zone 1 signal-to-noise ratio verses cone angle for the same target only 70 meters away. Another parameter varied in the study was the effect of increasing the length of the light cone on the zone 1 signal-to-noise ratio. As shown in Figure 14 increased cone length increases the signal-to-noise ratio somewhat lineraly.

Another study was to determine the effect of the signal-to-noise ratio for both zone 1 and 2 varying the concentrator to detector plane distance. All other parameters held constant are shown in Figure 10. As shown in Figure 15 the signal-to-noise ratio for zone 1 varies slowly with large changes in detector distance. This is due to the fact that the light illuminating the zone 1 area is coming in at near normal incidence while in zone 2 the light is coming in at a very shallow angle. Therefore zone 2 signal-to-noise ratio is very sensitive to the detector distance (see Figure 16).

Our third study was to determine the effect of increased detector area on the signal-to-noise ratio. As shown in Figures 17 and 18 the optimum detector area is favored for smaller detectors. However as a practical limit detectors cannot be smaller than 20 square microns.

The last study was to determine the effect of various target parameters on the signal-to-noise ratio. The targets in this study all have surface areas of 10 square meters and temperatures of 400 degrees K. The signal-to-noise ratio was computed versus detector distance. The optical system parameters are shown in Figure 10. As shown in Figure 19 the target must be at a range of 2000 meters or less for the zone 1 signal-to-noise ratio to be greater than one. For zone 2 however the target range must be less than 200 meters (see Figure 20).

The result of this study have pointed out a very significant fact. That is the zone 2 detectors cannot lie in the same plane as the zone 1 detectors because of the great differences in the signal-to-noise ratios and the fact that they vary

Background illumination has been omitted from these computations (i.e., the targets are assumed to be observed at night) because of the wide variety of background scenarios these considerations are beyond the scope of this effort. However, we have computed the area subtended by the FOV of the MAO eyelets at the target range. The FOV is computed by determining the largest angle at which light can enter the concentrator and not be reflected back out. For a detailed discussion of this principle see the MAO primer in Appendix A. From the tangent of the acceptance angle multiplied by the target range the radius of the area is computed. Although not used in this program the areas can be multiplied by a background intensity to compute the signal to background ratios observed by the MAO eyelet.

The incident power flux from the target is magnified going through the light concentrators (eyelets). The magnification is computed by taking the ratio of the entrance pupil area and the exit pupil area (Ain/Aout). The input parameters used to characterize the light concentrators are: 1) half-angle of the light cone (θ in degrees), 2) length of the light cone (1 in micrometers), and 3) the entrance pupil radius (R_{in} micrometers). The exit pupil (R_e) is calculated by: $R_e = R_{in} - \tan\theta(1)$. It is assumed that the reflectivity of the cone walls is unity.

The power flux incident on the detector plane is computed as follows. Using the extreme exit angle (θ) computed for zones 1 and 2 the increased radius (R) of the spot illuminated on the detector plane is calculated by:

$$R = d \tan\theta$$

where d is the distance between the exit pupil and the detector plane.

The radius of the spot is then the sum of R plus the exit pupil radius. The power flux in each zone is calculated as the ratio of the exit pupil/spot areas multiplied by the magnified incident power flux.

The signal-to-noise ratio for the detectors in both zones 1 and 2 is computed as follows. The detector characteristics are taken as input data:

1) Detector surface area (A_d)
2) Detector sensitivity (long and short wavelength cut-off)
3) Detector time constant (to compute (D*)

$$\text{SNR (Zone 1)} = \text{Power Flux (Zone 1)}/(\text{Ad}\ \ D^*)^{1/2}$$

$$\text{SNR (Zone 2)} = \text{Power Flux (Zone 2)}/(\text{Ad}\ \ D^*)^{1/2}$$

The code is interactive with a menu to prompt input data and is written in a modular format (in Fortran) consisting of eight subroutines. The first three routines accept input data for the target parameters, MAO system parameters, and detector system parameters. The MAO system parameter routine also computes the magnification ratios of the light concentrations (eyelets) as well as the extreme acceptance and exit angles for the eyelets broken down into two distinct zones. Zone 1 is computed as that area illuminated by light which originates in the exclusive FOV of an eyelet, while zone 2 is computed as the area illuminated by light which originates from the total FOV of an eyelet and overlaps with the TFOV of the neighboring eyelets. A detailed description of the assumptions and computational algorithms used in this code is discussed below (also see Appendix A, MAO Primer). The fourth and fifth routines compute the field-of-view of the MAO at the target range and the projected area of the FOV on the detector plane for each eyelet. The sixth routine computes the total radiated power emitted by the target and the targets spectral radiant emittance integrated over the detector's sensitive wavelength region. The seventh routine takes the incident radiant power and projects it through the optical system to compute the power flux incident on the detector array for both zone 1 and zone 2. The last routine computes the signal-to-noise ratio for the optical system based on the computed power flux and given detector parameters.

The code only examines one eyelet. However, the assumption is made that the zone 2 detector area SNR will be the same for all eyelets (with overlapping FOV) viewing the same target. Therefore we can (in effect) examine several eyelets at once.

B. Computation Algorithms and Assumptions

For the purposes of these calculations the targets are assumed to be point source black body emitters (i.e., they are at distances much greater than their dimensions). The target input parameters are then: 1) target surface area (in square meters), 2) target range (in meters), and 3) target temperature (in degrees K). The total spectral radiance of the target (in watts into 2π) is calculated by integrating Planck's function over the wavelength range defined by the sensitive wavelength range of the detectors and multiplied by the target area. The incident radiant power flux (in watts/cm^3) is computed by calculating the area of a sphere created using the target range as the radius and dividing into the total emitted spectral radiance of the target.

```
  oo  oo  oo  oo  oo  oo  oo  oo  oo  oo  oo
oo  oo  oo  oo  oo  oo  oo  oo  oo  oo  oo
  oo  oo  oo  oo  oo  oo  oo  oo  oo  oo  oo
oo  oo  oo  oo  oo  oo  oo  oo  oo  oo  oo
  oo  oo  oo  oo  oo  oo  oo  oo  oo  oo  oo
oo  oo  oo  oo  oo  oo  oo  oo  oo  oo  oo
```

Figure 9 (a)

```
  xo  xo  xo  xo  xo  xo  xo  xo  xo  xo  xo
oo  oo  oo  oo  oo  oo  oo  oo  oo  oo  oo
  xo  xo  xo  xo  xo  xo  xo  xo  xo  xo  xo
oo  oo  oo  oo  oo  oo  oo  oo  oo  oo  oo
  xo  xo  xo  xo  xo  xo  xo  xo  xo  xo  xo
oo  oo  oo  oo  oo  oo  oo  oo  oo  oo  oo
```

9 (b)

Arrangement of Detectors on Optic RAM

they are displayed in various matrices.

The available choices are:

1. 128 x 64 (black and white)
2. 512 x 64 (smoothed)
3. 512 x 64 (grey)
4. 512 x 128 (black and white)
5. 640 x 128 (smoothed)
6. 640 x 128 (grey)

There are two areas in the chip which are filled by detectors. Each has the size of 5mm x 2mm. They are separated from each other by a 120μm wide gap. The aspect ratio of each area is 5:1, while the detector matrix is 256 x 128, which is 2:1. Therefore the distances between rows is different from the distances between detectors. To complicate things even more, the distance between detectors in a row is not equal either. Figure 9 shows how they are arranged. There are obviously certain holes, which can be filled in by software, depending what is in the neighboring pixels. This is the way 2 through 6 are generated. The 128 x 64 matrix is generated by leaving every other detector out as indicated by "0" in Figure 9b (and "x" detectors are read). The software developed by us allows the reading out of the image in binary form, "0" implying presence of intensity while "1" means darkness. Only the 128 x 64 image is read out, which means no holes are filled in. The printout is done consecutively, rather then with spaces. For this reason the binary image looks somewhat distorted to an observer. However, the intention is to provide numbers for our recognition system, which can be manipulated. It should always be born in mind when looking on our bit maps or even image printouts that it is not the object to produce an image but a numerical display of reality.

III. COMPUTER MODEL

A. Description

In the course of this research effort we have written a computer code to model the MAO system with respect to target characteristics, MAO architecture, and detector parameters. The purpose of the code is to enable us to do a parametric study of the MAO system. This data has enabled us to design the optimum MAO system and determine what target characteristics the system can identify based on signal-to-noise considerations.

(soda-lime) glass fibers is arranged to form the desired matrix (hexagonally closed packed array). The fibers are a few centimeters in length and are anywhere from 10 to 100 microns in diameter and placed in the array so that the area obtained by the sum of all the fibers is less than or equal to half the area of the entire matrix (i.e., the fibers are spaced no closer together than their diameter). The fibers are held in the matrix at both ends. Then a molten lead-based (opaque) glass is poured into the matrix until a block of solid glass is formed. After cooling the glass block is cut and ground into thin slices. To create the capillaries or microchannels the glass is then etched. The etching process only attacks the soda-lime glass fibers leaving the leaded glass intact producing the desired holes.

There are two modifications required to this process to create the ideal MAO element: 1) the holes in the matrix must be conical or funnelled (typical cone angles are 1-5 degrees) and 2) the matrix must be curved (typical radius of curvature 10-100 centimeters). To create conical holes it is proposed to use a modified etching process and/or tapered fibers.

The matrix is curved by a slumping process. The process works as follows: A graphite mold is machined with the correct curvature. The flat plate is inserted in the mold and placed in a furnace and heated until the glass softens and conforms to the shape of the mold. This process is usually done before etching. The finished product (a miniscus) is then ground flat on one side producing a plano-convex glass matrix of cylindrical or eventually funnelled holes (concentrators).

D. Software for Operation of the MAO Camera

The operation of the optical RAM is based on the software which was developed by the manufacturer of this device. Since the RAM was intended to be used in connection with a lens as a TV camera, the software for such a camera needed to be modified by us to suit our purposes especially to produce a binary image. Such a binary image is the basis of all recognition schemes.

The camera has a IS32A chip which was originally designed as a memory only. The operations program has refresh, interrupt and transmit modes. In the refresh mode the individual elements which are capacitatively coupled to the photosensitive element are charged to 5V. Under the influence of light the tiny capacitors are discharged. In the transmit mode the memory locations are read either in sequence or randomly as desired and transmitted to the computer, where

BITMAP LISTING OF B:PICTA.DAT

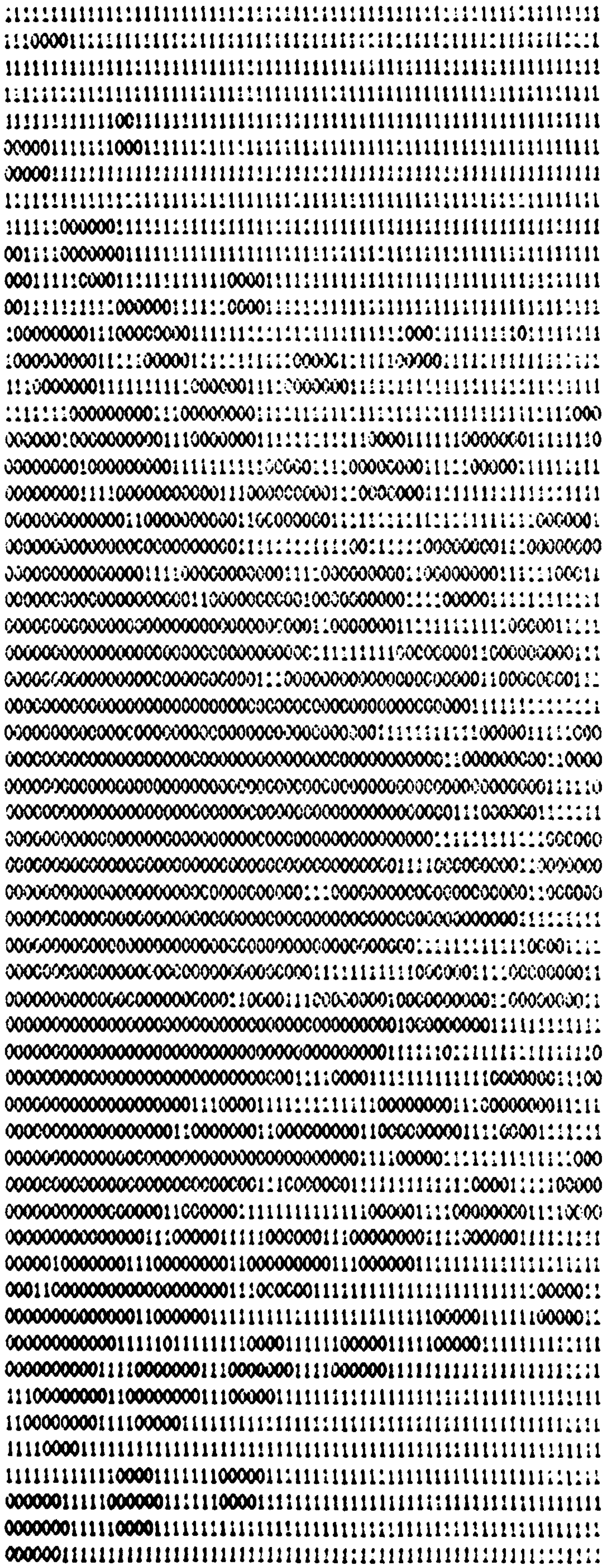


Figure 8

Binary image showing fully illuminated, partly illuminated and overexposed footprints

in. As can be seen, corners have a tendency to be filled out. This can be explained by cross talk between the individual eyelets since they do not have a reflective coating yet. We hope to eliminate this problem as soon as we have a coated MAO mask available.

Figure 8 shows a binary image showing some footprints grown together and some isolated ones. The number "0" indicates light present while the number "1" indicates darkness. The footprint of an individual light horn which is completely and uniformly filled with light and not overexposed is 4 rows high. The two center rows should have nine "0" in it while each of the outer rows should have eight. The fact that there are only 4 rows but 9 columns has to do somewhat with the unique way the detectors are arranged on the optical RAM.

C. Fabrication of MAO MAsk

To create the ideal MAO element an array of light concentrators (light horns) evenly spaced on a matrix of opaque material is required. In addition the array must be laid down on a curved surface so that the individual concentrators "look" into different solid angles. Ideally the curvature and FOV of the concentrators is arranged so that the FOV of an individual concentrator is overlapped to some extent by all of its closest neighbors. Perhaps the most challenging aspect of the element fabrication is the requirement that the mask be small enough to interface with the detector array. (Typical dimensions of detector arrays are millimeters in over all size with the individual detectors less than 100 square microns.) Therefore the size of the individual concentractors must lie in the range of 30–100 microns in diameter and 0.5 to 1.0 millimeters in length while the overall size of the element is on the order of 10 x 50 millimeters. Other required features include the precision in which the light concentrators are spaced (uniformly) in the matrix, the surface quality of the concentrator cones to enhance reflectivity, and the spherical symmetry of the surface of the element.

The technology used consists of a glass matrix and was subcontracted to Galileo Electro-Optics in Sturbridge, Massachusetts. At present they are producing glass capillary arrays (for filtration purposes - GCA) and micro-channel plates (for image intensifiers - MCP) within the dimensional range we are seeking. However there proved to be extensive modifications required in order to produce the ideal MAO element we require.

A typical GCA or MCP is fabricated in the following manner. A bundle of

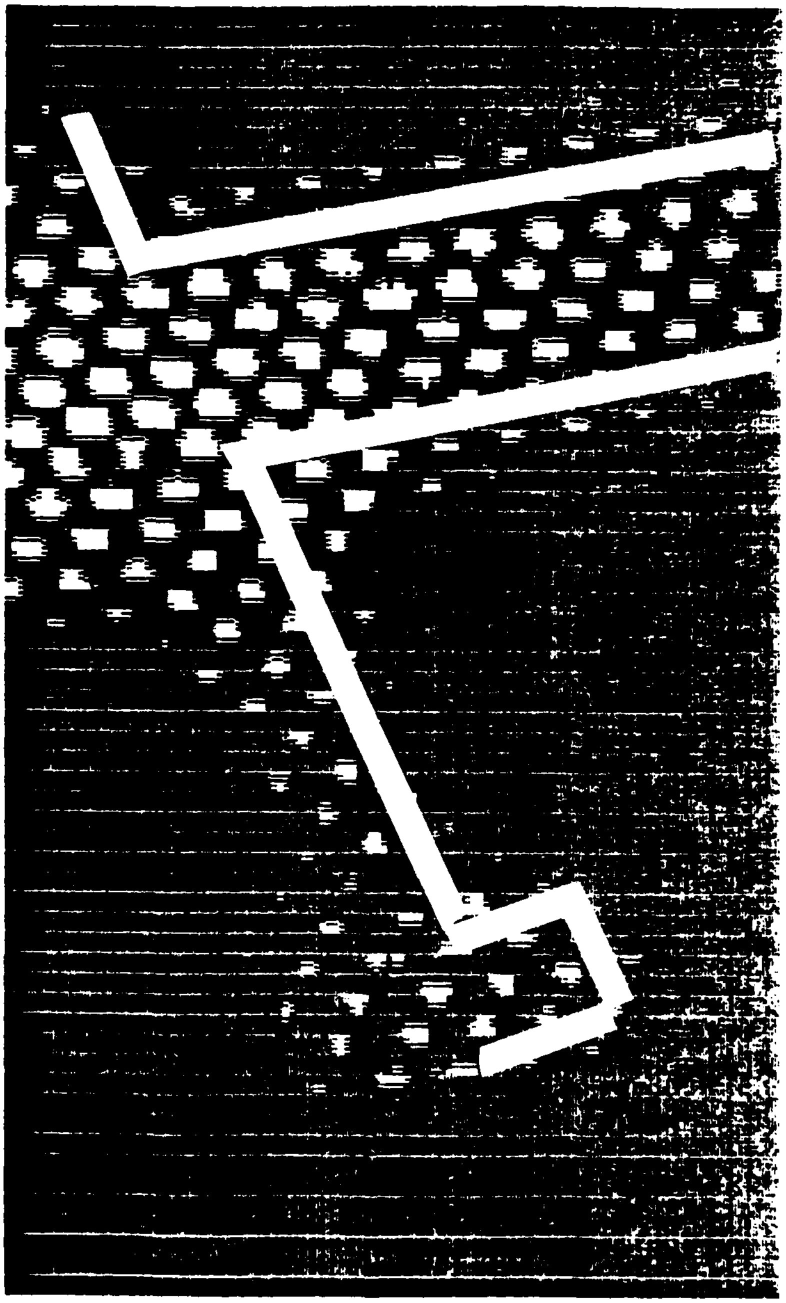


Figure 7

Same as Figure 6 with outline drawn in

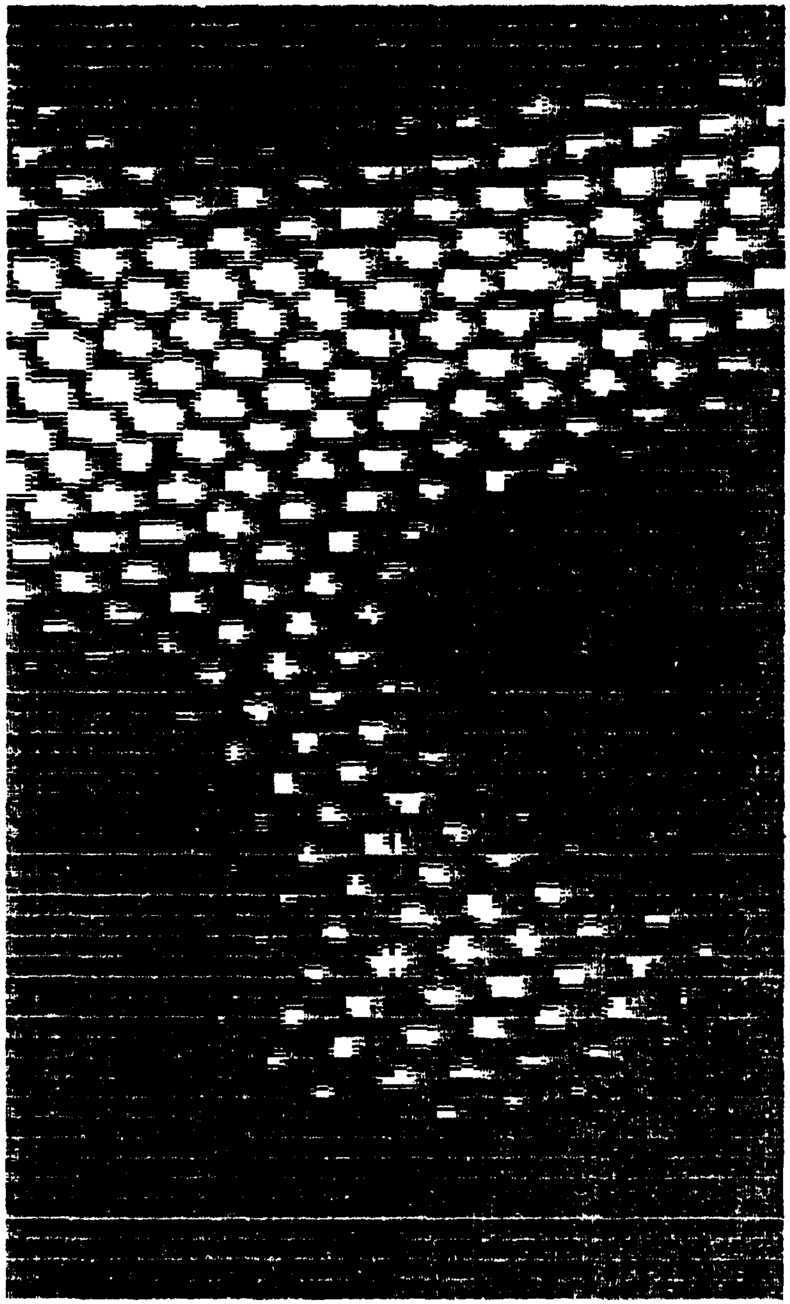


Figure 6c

Airplane - 16 millisec.

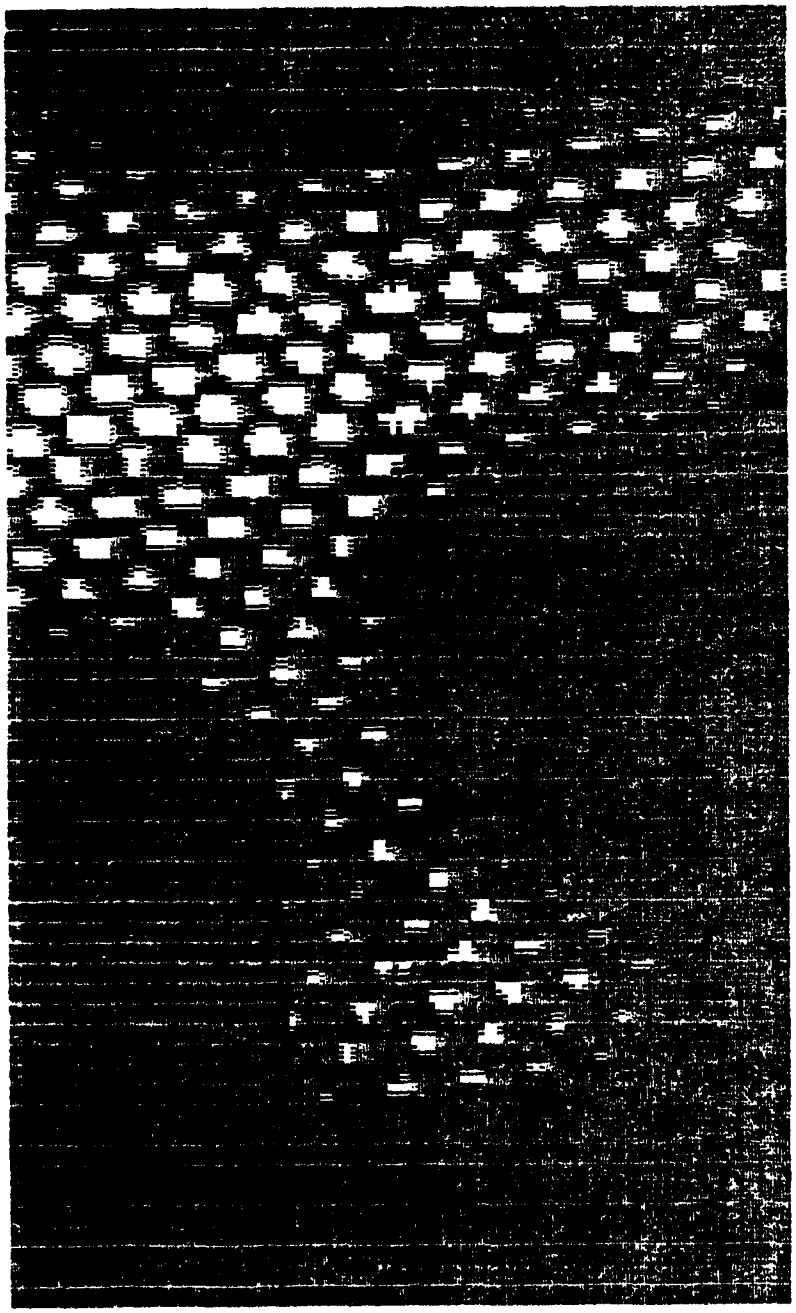


Figure 6b

Airplane - 12 millisec.

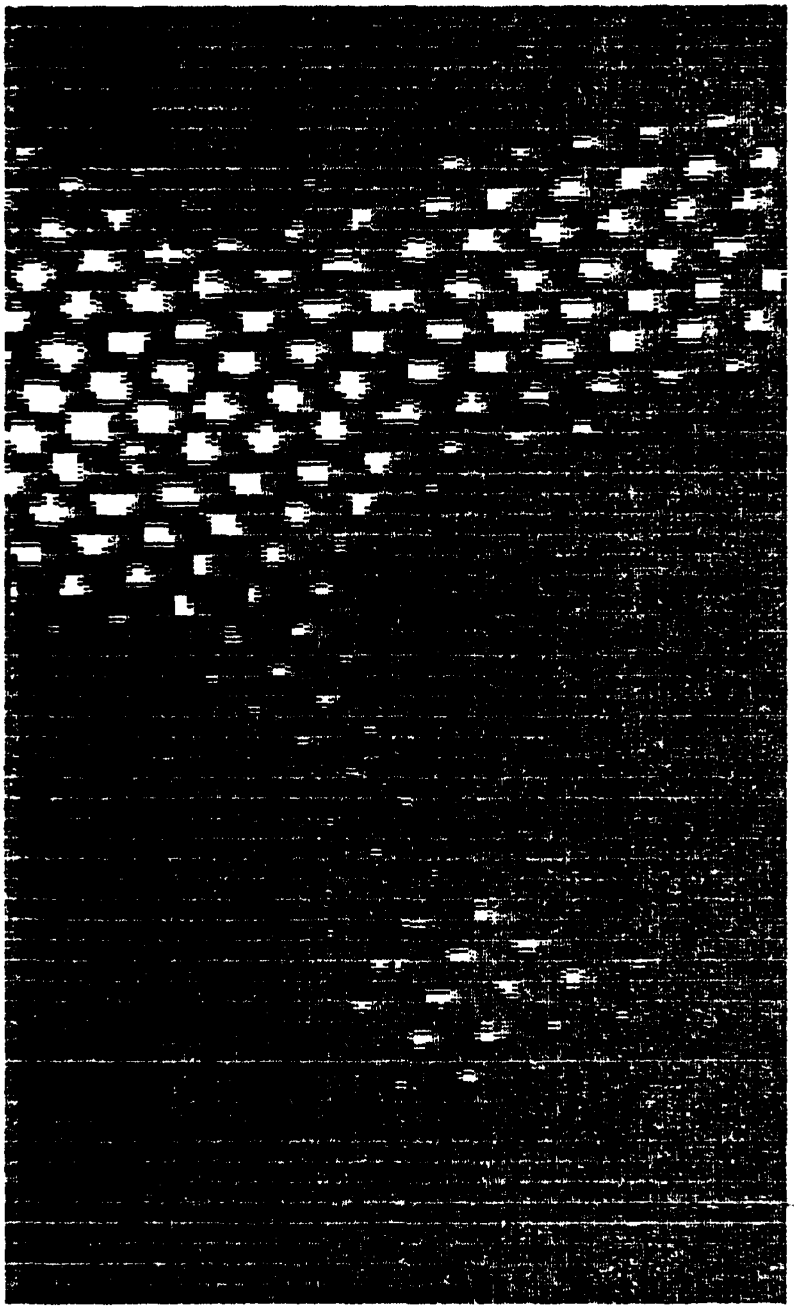


Figure 6a

Airplane - 10 millisec.

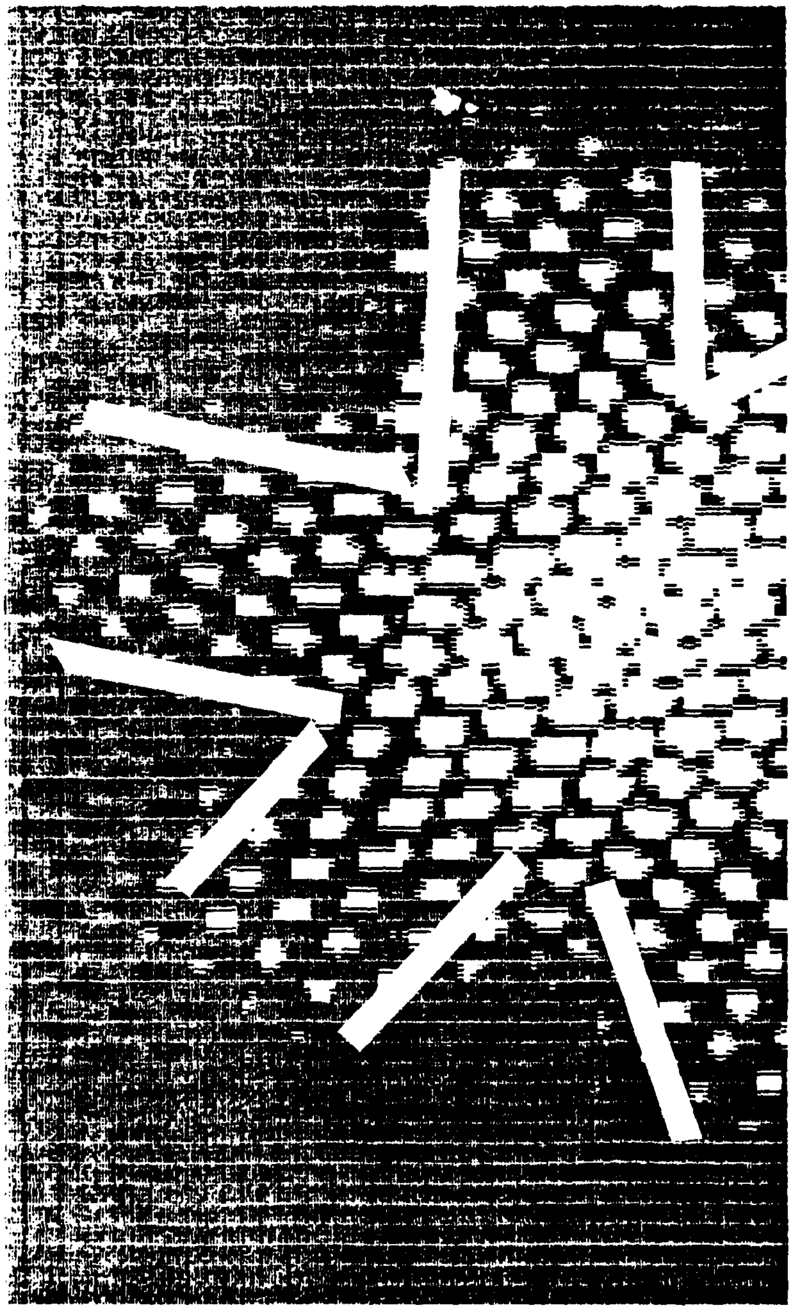


Figure 5

Same as Figure 4 with outline drawn in

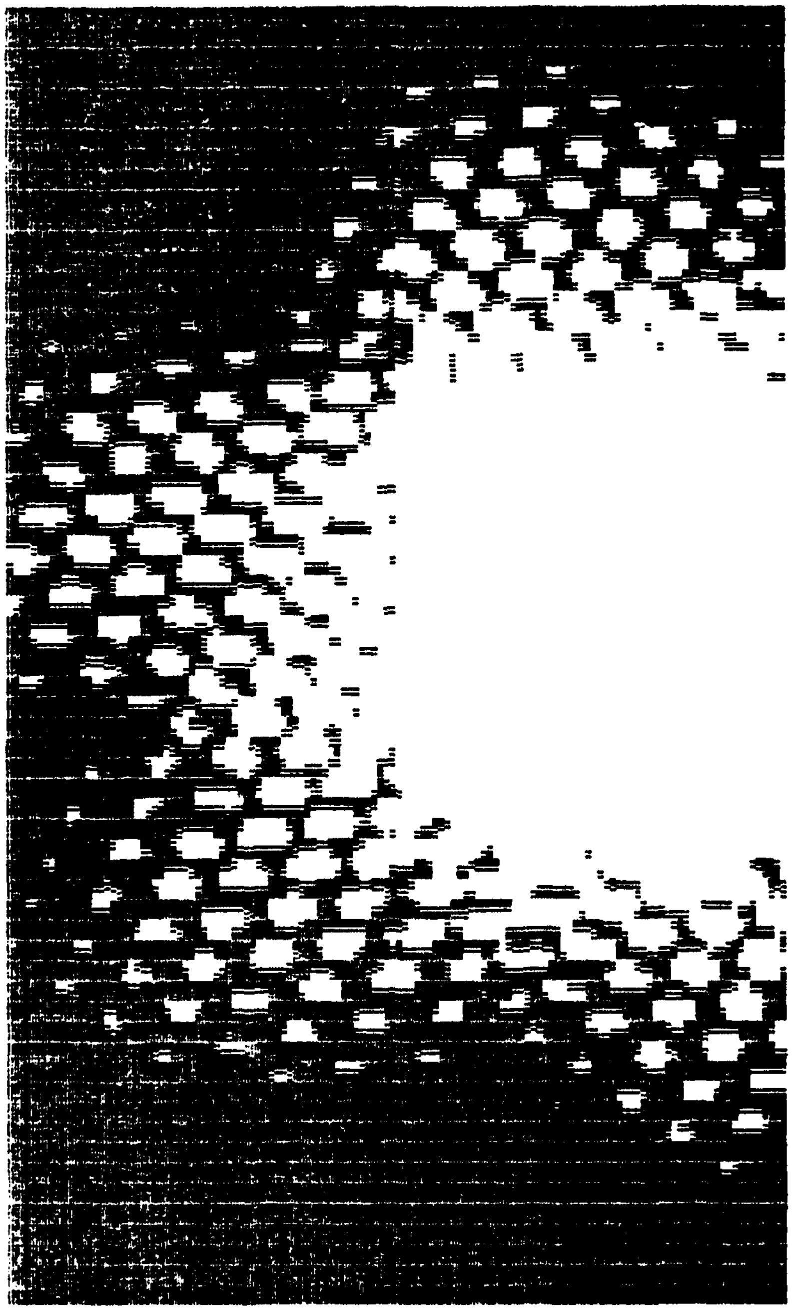


Figure 4e

Six Legged Cross - 56 millisec.

```
1.) TARGET PARAMETERS:
      SURFACE AREA:                         [SQUARE METERES]  10.0
      RADIUS:                                       [METERS]  1.78
      RANGE:                                        [METERS]  .100E+04
      TEMPERATURE:                             [DEGREES K]    400.
2.) OPTICAL SYSTEM PARAMETERS:
      HALF ANGLE OF LIGHT CONE:                    [DEGREES]  1.00
      LENGTH OF LIGHT CONE:                        [MICRONS]  800.
      ENTRANCE PUPIL RADIUS:                       [MICRONS]  100.
      EXIT PUPIL RADIUS:                           [MICRONS]  86.0
      MAGNIFICATION RATIO:                                    1.35
      ZONE 1 EXTREME ENTRY ANGLE:                  [DEGREES]  13.1
      ZONE 1 EXTREME EXIT ANGLE:                   [DEGREES]  15.1
      ZONE 2 EXTREME ENTRY ANGLE:                  [DEGREES]  60.4
      ZONE 2 EXTREME EXIT ANGLE:                   [DEGREES]  88.4
3.) DETECTOR SYSTEM PARAMETERS:
      SURFACE AREA:                        [SQUARE MICRONS]   64.0
      DISTANCE TO OPTICAL SYSTEM:                  [MICRONS]  50.0
      LONG WAVELENGTH CUTOFF LIMIT:                [MICRONS]  5.00
      SHORT WAVELENGTH CUTOFF LIMIT:               [MICRONS]  4.00
      TIME CONSTANT:                         [MICRO-SECONDS]  .500E+04
      DSTAR:                                 [CM HZ**.5 / W]  .100E+09
4.) TARGET - OPTICS CORRELATIONS:
      ZONE 1 ACCEPTANCE AREA AT TARGET:  [METERS**2]  .170E+06
      ZONE 2 ACCEPTANCE AREA AT TARGET:  [METERS**2]  .970E+07
5.) OPTICS - DETECTOR CORRELATIONS:
      ZONE 1 AREA AT DETECTOR PLANE:    [MICRONS**2]  .311E+05
      ZONE 2 AREA AT DETECTOR PLANE:    [MICRONS**2]  .105E+08
6.) TARGET PHOTOMETRIC PROPERTIES:
      TOTAL TARGET RADIANT EXITANCE:   [WATTS/CM**2] .1716E-02
          NOTE: EQUAL TO THE TARGETS SPECTRAL RADIANT
          EXITANCE, INTEGRATED OVER WAVELENGTH.
      TOTAL TARGET RADIANT FLUX OR POWER:     [WATTS] 171.6
          NOTE: TOTAL POWER RADIATED FROM TARGET INTO THE
          SEMI-INFINTE HALF SPACE OF THE DETECTOR.
7.) SYSTEM CORRELATION PHOTOMETRIC PROPERTIES:
    ENTRANCE PUPIL INCIDENT RADIANT POWER: [WATTS] .8578E-12
          ENTRANCE PUPIL POWER FLUX:          [WATTS/CM**2] .2731E-08
      DETECTOR SURFACE POWER FLUXES, BY ZONES
         ZONE 1 POWER FLUX:               [WATTS/CM**2] .2757E-08
         ZONE 2 POWER FLUX:               [WATTS/CM**2] .8185E-11
8.) SIGNAL TO NOISE RATIOS FOR THE CENTRAL EYELET:
      ZONE 1 SIGNAL TO NOISE RATIO:     4.8738
      ZONE 2 SIGNAL TO NOISE RATIO:     .14470E-01
          NOTE: ZONE 1 SNR IS CENTRAL EYELET.
                ZONE 2 SNR IS THE 6 SURROUNDING EYELETS.
```

Figure 10

Input Data for Sample Calculation

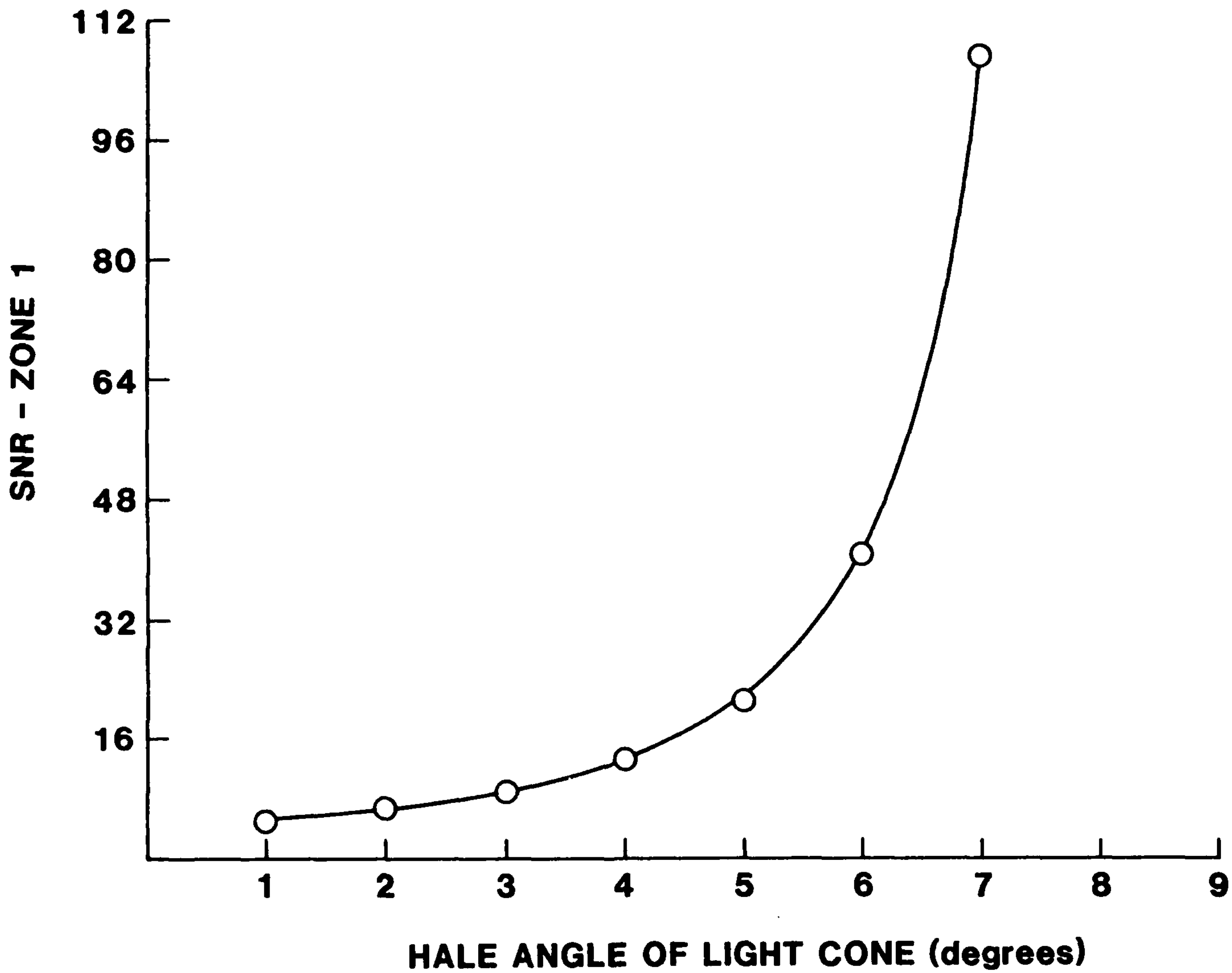


Figure 11 - SNR Zone 1 vs Half Angle of Light Cone, Range 1000 meters

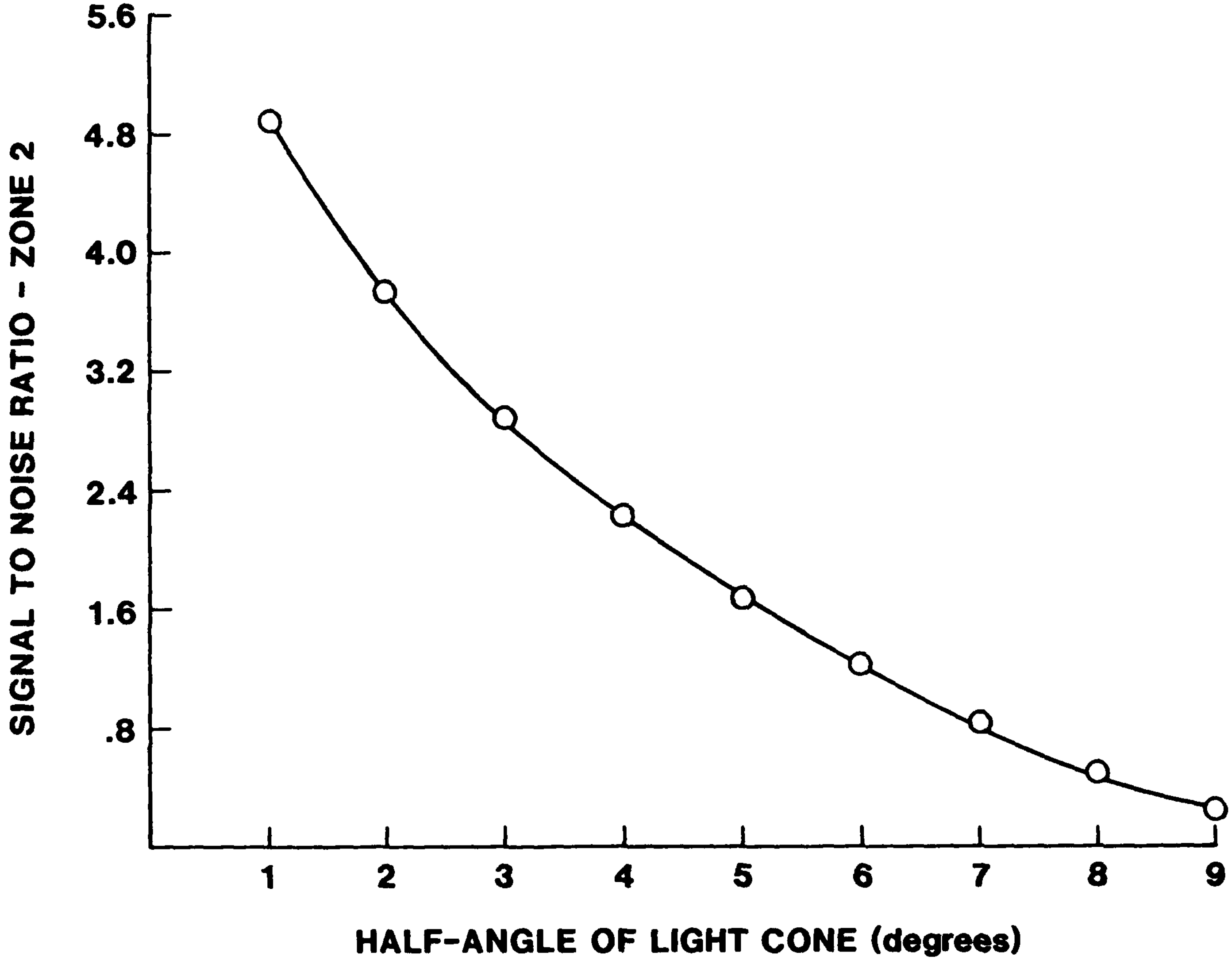


Figure 12 - SNR Zone 2 vs Half Angle of Light Cone, Range 1000 meters

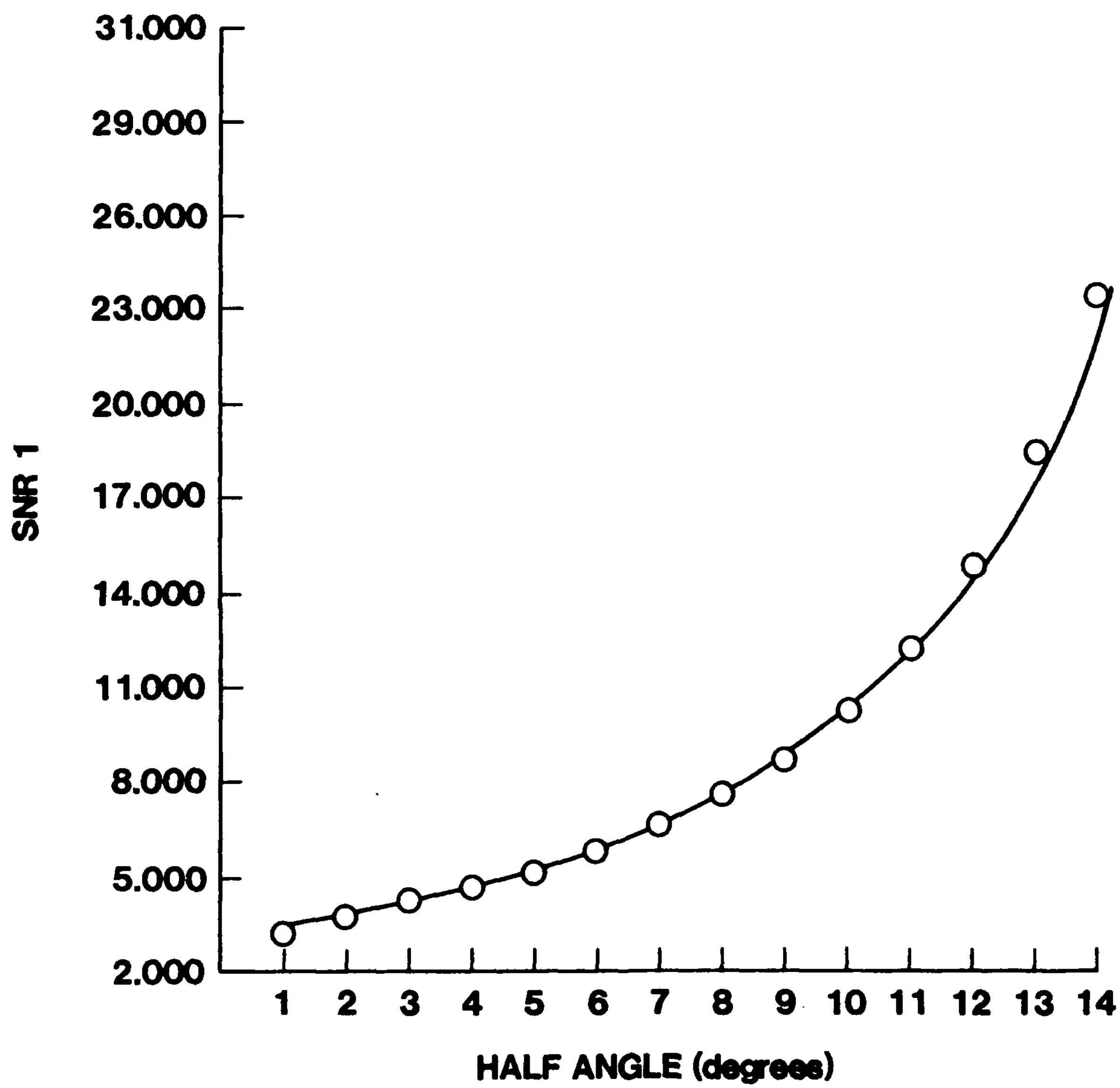


Figure 13 - SNR Zone 1 vs Half Angle of Light Cone, Range 70 meters

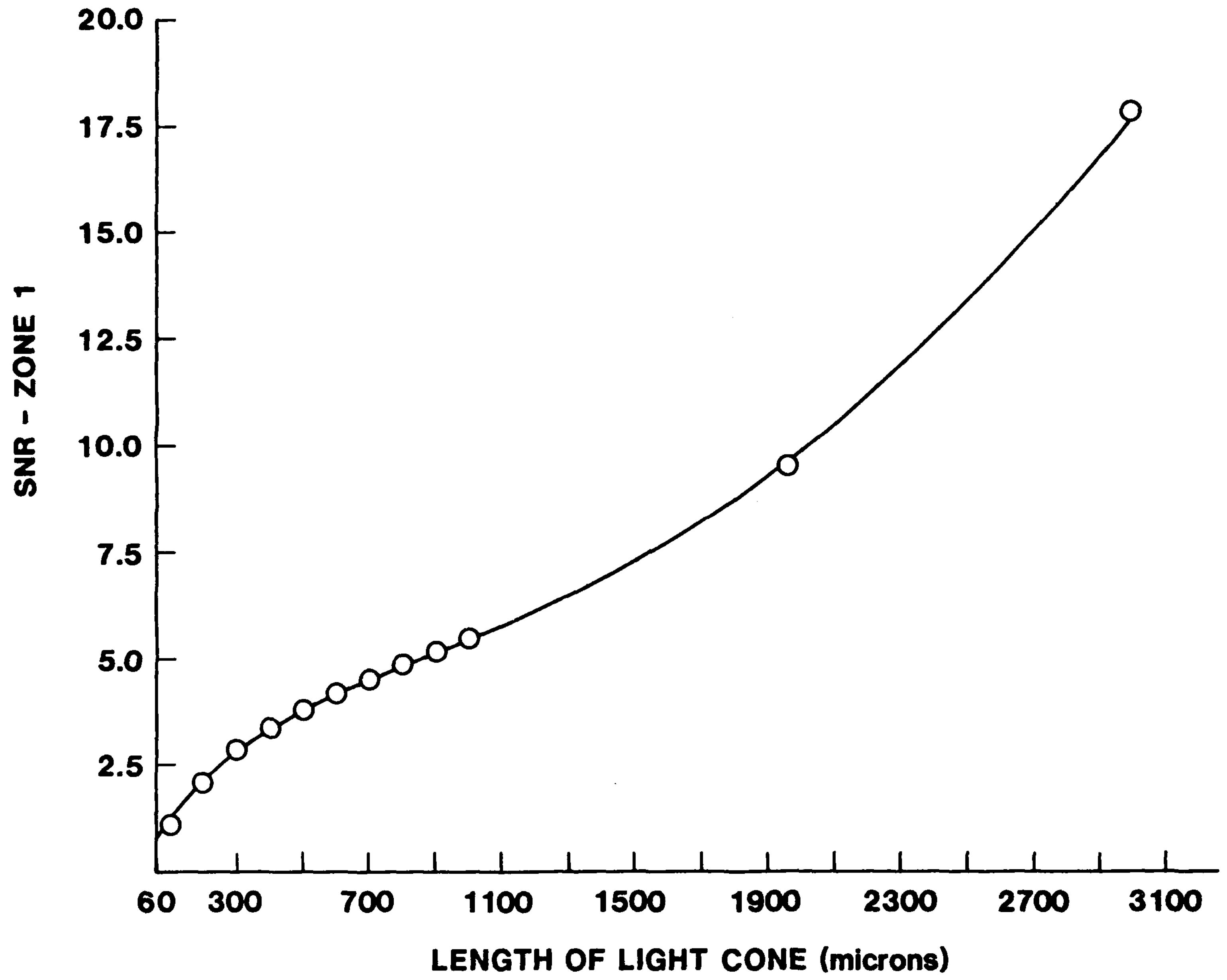


Figure 14 - SNR Zone 1 vs Length of Light Cone (Cone Angle 1°), otherwise like Figure 10

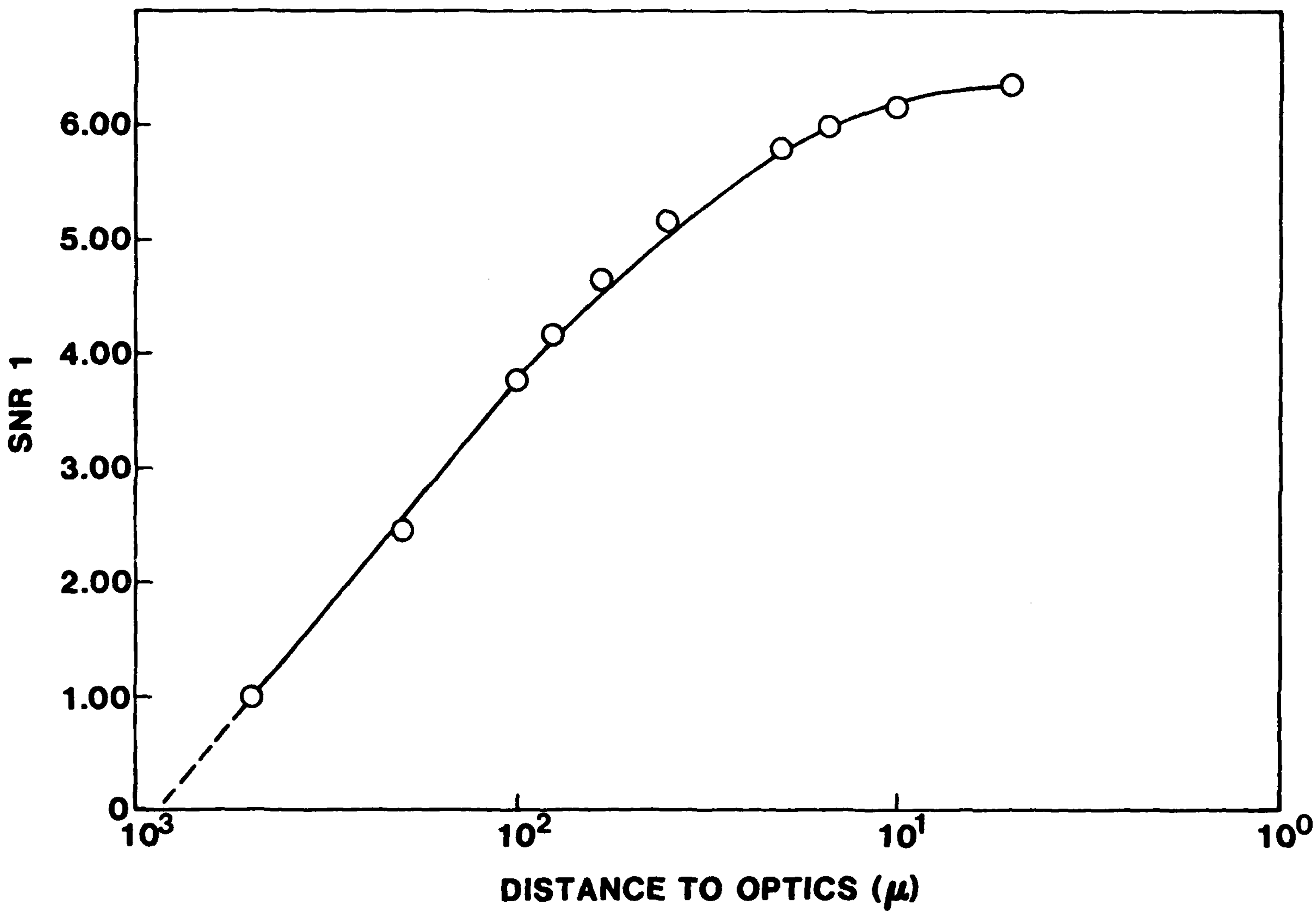


Figure 15 - SNR Zone 1 vs Distance Between Exit Aperture and Detector Plane

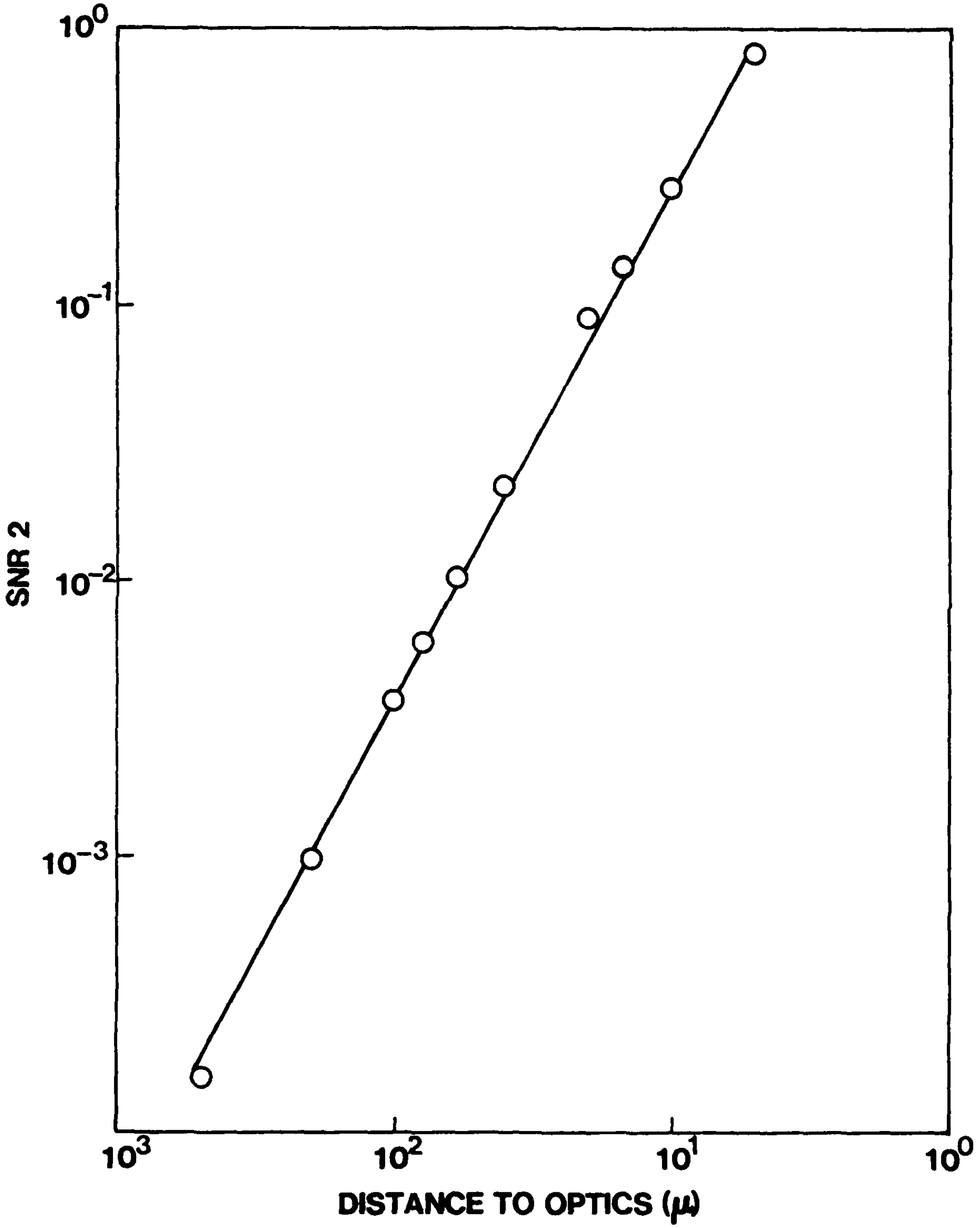


Figure 16

SNR Zone 2 vs Distance Between Exit Aperture and Detector Plane

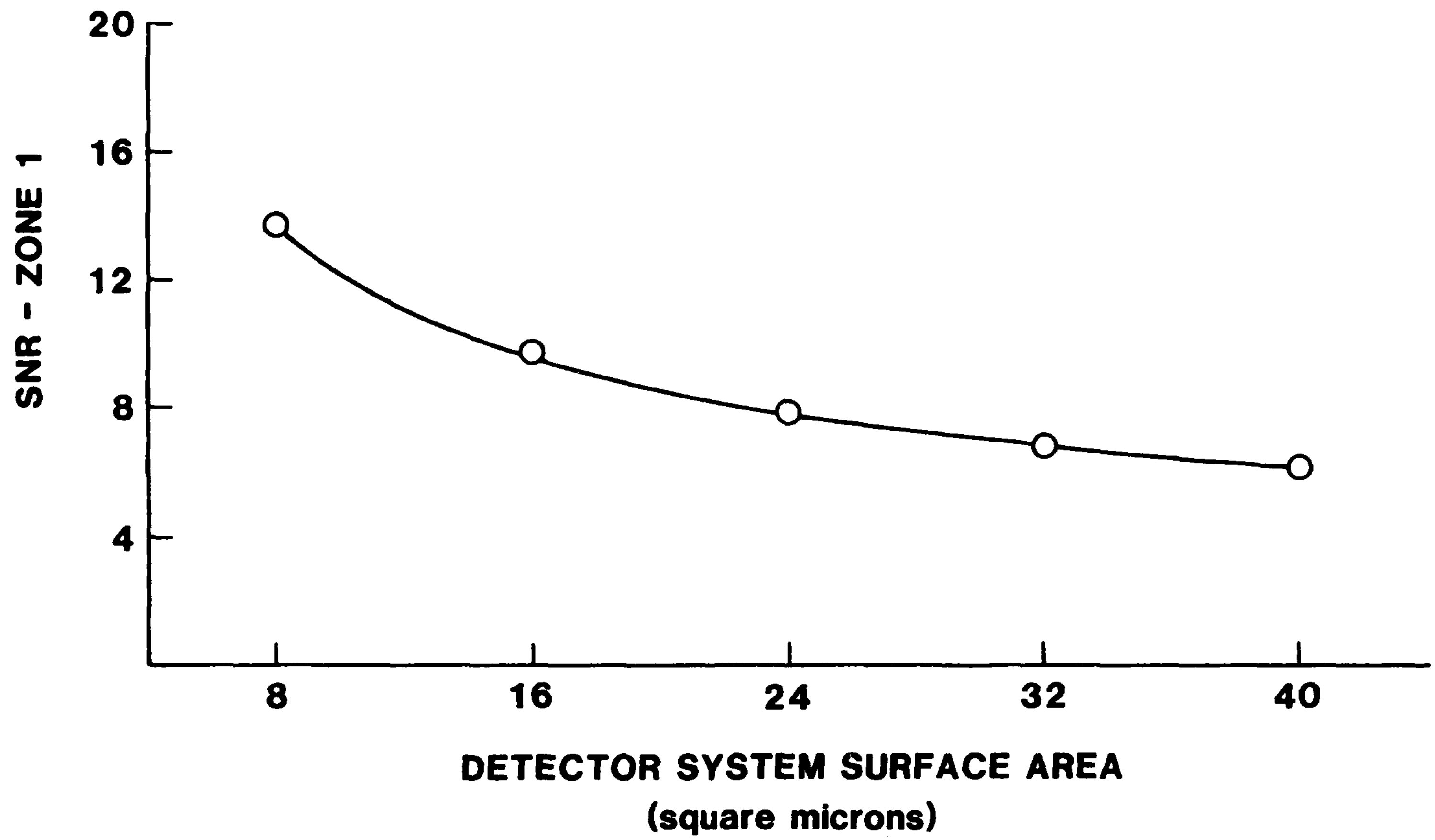


Figure 17 - SNR Zone 1 vs Detector Area

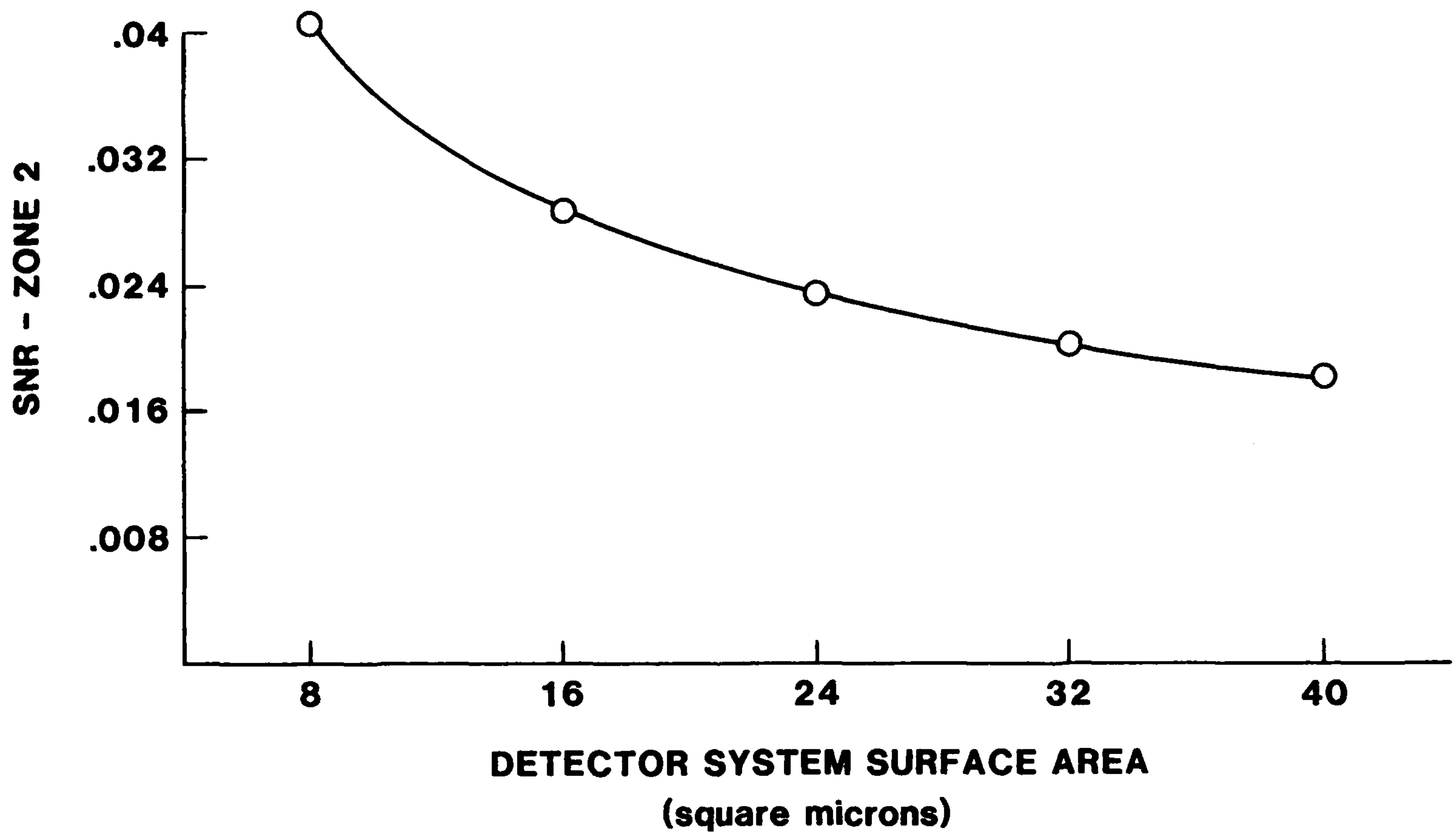


Figure 18 - SNR Zone 2 vs Detector Area

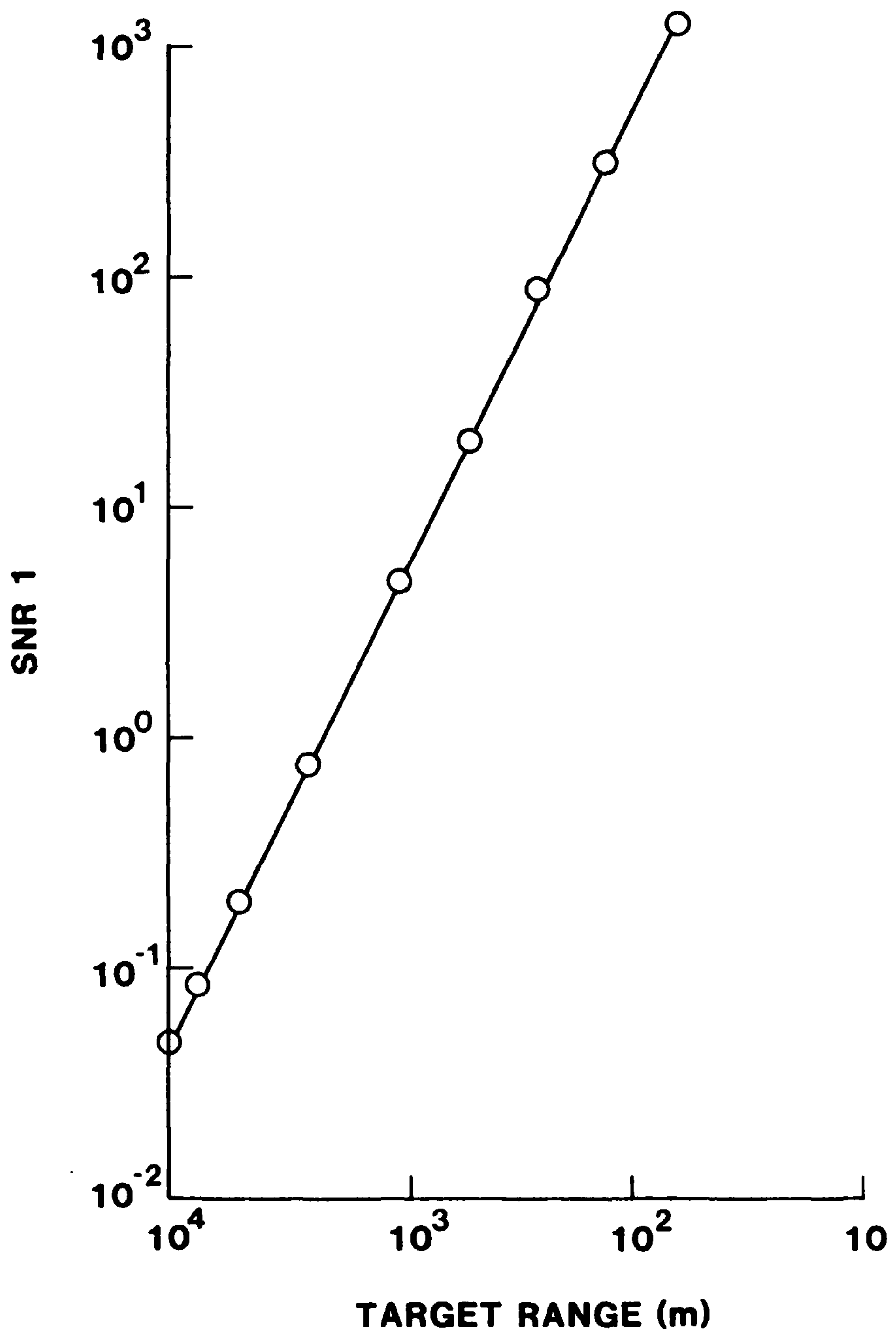


Figure 19 - SNR Zone 1 vs Range

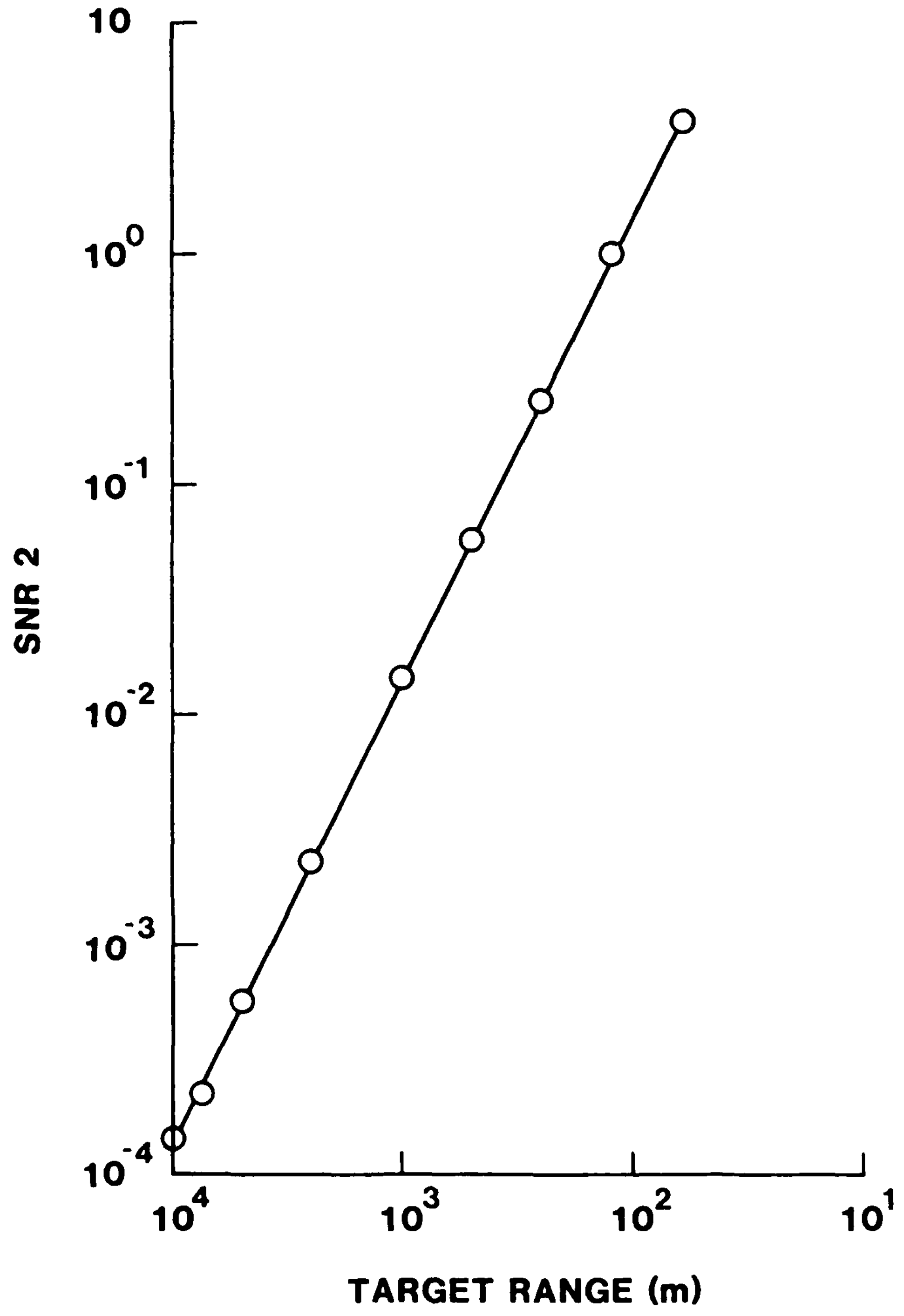


Figure 20 - SNR Zone 2 vs Range

reciprocally. In order to increase the signal-to-noise ratio on zone 2 to be equal to zone 1 and zone 2 "footprints" has to be of equal size. One way to accomplish this is to arrange the detector array like a cup. In this configuration the cup would be in the shape of a truncated cone. The cone angle would be normal to the exit angle for zone 2. (The top of the cup would be placed in contact with the concentrator plate.) The depth of the cup would be chosen so that the area of the bottom would be equal to the area of the sides. The zone 1 detectors would be placed in the bottom of the cup and the zone 2 detectors on the walls. This configuration actually exists in some insect eyes. There are some speceies that have fiber shaped detectors with sensors on the walls and bottom of the fiber. The reason for this have now become clear.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. Achievement of Phase I

a. Experiment

An operating MAO camera was built during Phase I. The FOV of this camera is 4 degrees and the achieved resolving power is 0.25 degrees. Single frame exposures as short as 1 msec have been taken. Continuous update of the frames compatible with the transmission baud rate to the computer was accomplished. Exposure times can be set at a fixed value, or the system can automatically select the correct exposure time.

The data collected by the camera are digital. They can be printed out as a binary map, resembling the binary image of the object seen or they can be printed out by representing each pixel by a short line of a length proportional to the gray level.

The experimental results of Phase I show that it is technically feasible to build a MAO camera, having a large number of eyelets, in this case about 360, served by an even larger number of detetors, namely 128 x 256.

b. Design

A computer program allowing the input of all conceivable combinations of geometrical configurations and detector configuration was developed. It allows the computation of the signal-to-noise ratio of these combinations. This program will be a valuable aid in designing advanced MAO systems.

c. New Concepts

During the work on Phase I, two new concepts were generated. One pertains to application of the MAO concept to x-rays. A patent disclosure was separately submitted to ONR.

The second concept was named the Military Matrix. It is described in detail in the Phase II proposal.

Appendix A

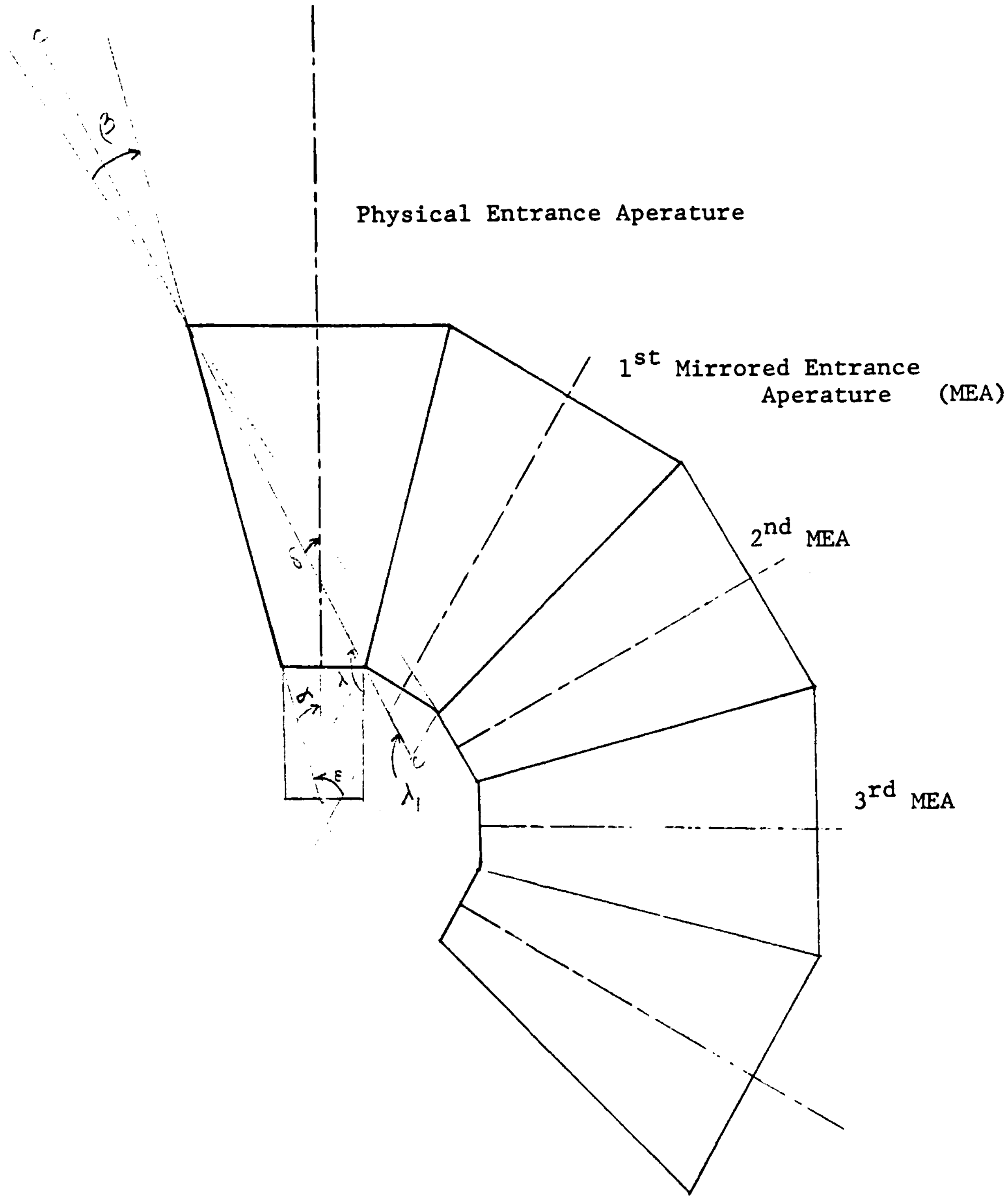


Figure 6 Non Overlapping FOV

or small cone angles (2α) the location of the entrance and exit apertures can be pproximated by two circles, an entrance aperture circle having a radius ($R + r$) nd an exit aperture circle having a radius (r). The maximum angle (γ) under hich the beam is not reflected out of the light horn is given by the tangent on the xit aperture circle as indicated in Figure 5.

The angle β is therefore

$$\text{Sin } \beta = \frac{r}{R + r}$$

nd the maximum FOV (γ)

$$\gamma = 2 \text{ arc sin } (\beta + \alpha)$$

However for the sake of easy manufacturing it is probably advantageous to ill the light horn and detector housing with a transparent material having efractive index of n. This increases the angle β somewhat to β'.

Since

$$\frac{\text{Sin } \beta'}{\text{Sin } \rho} = n$$

$$\text{Sin } \beta' = n \frac{r}{R + r}$$

herefore, for small angles

$$\gamma = 2 \ (\beta + \alpha) \approx 2 \left[n \frac{r}{R + r} + \alpha \right]$$

In summary, any ray intersecting the front surface of the light horn under n angle in respect to the optical axis, which is smaller than $2(\beta' + \alpha)$ will be unneled into the detector housing and detected. Rays intersecting under a large ngle will be reflected out of the front surface of the light horn.

The next question to be solved is under what angle (δ) a ray has to enter o that only the center detector will be illuminated. This condition determines he non-overlapped FOV (δ) of an individual light horn, while the angle γ ives the total FOV, some of which overlaps the FOV of the neighboring light horns.

In Figure 6 ray C has the largest possible angle δ with the optical axis, ithout being reflected from the light horn walls. It intersects with the walls f the detector housing under the angle λ. By proper selection of the efractive index n which fills the detector housing one can assure that $\lambda > \lambda_o$ here λ_o is the critical angle for total reflection. Therefore

$$\lambda > \lambda_0$$

$$\lambda = \frac{n_1}{n_2}$$

n_1 is the refractive index of the material between the detector and the detector ousing which should be chosen as small as possible while n_2 is the refractive

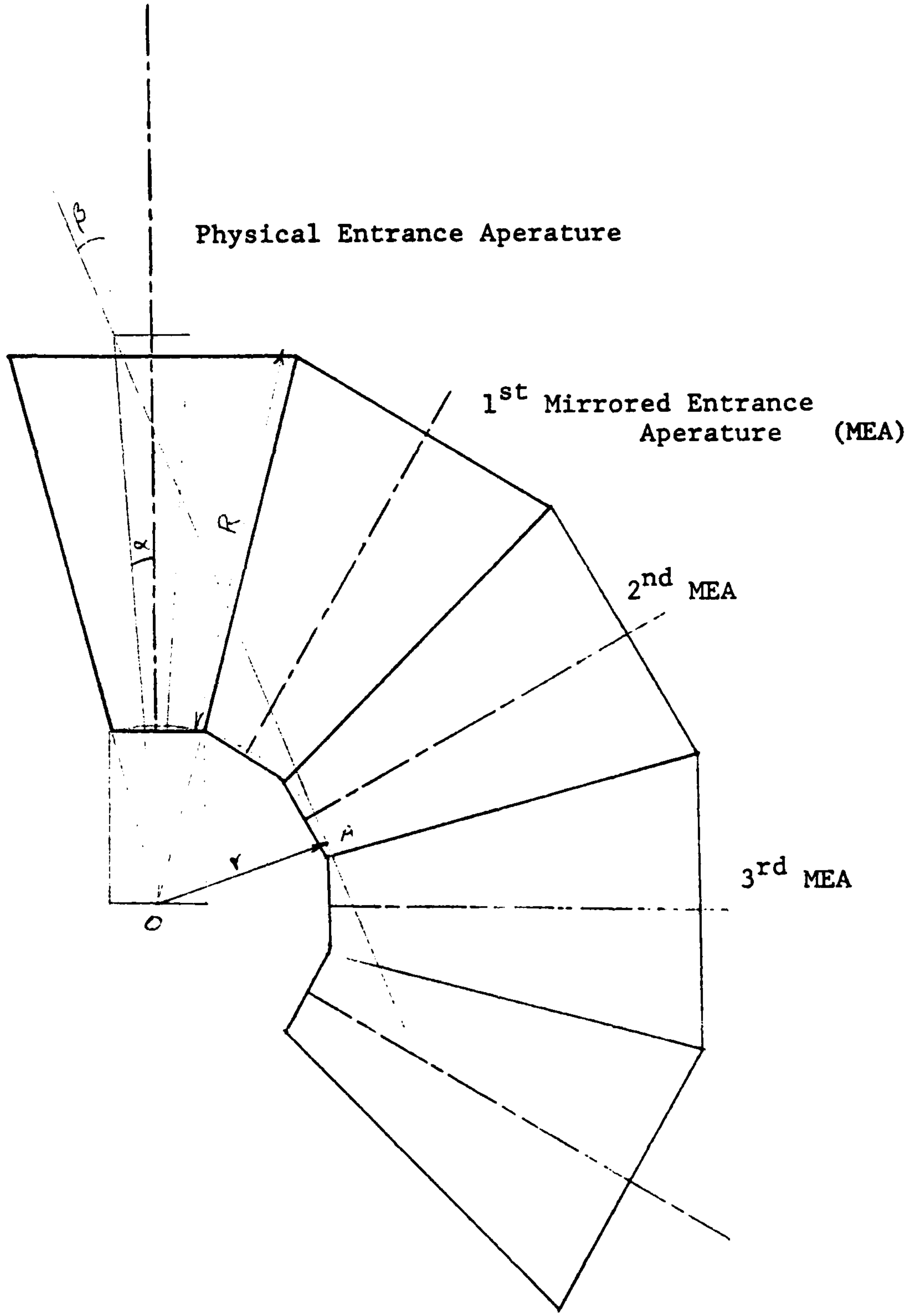


Figure 5   Light Horn Field of View

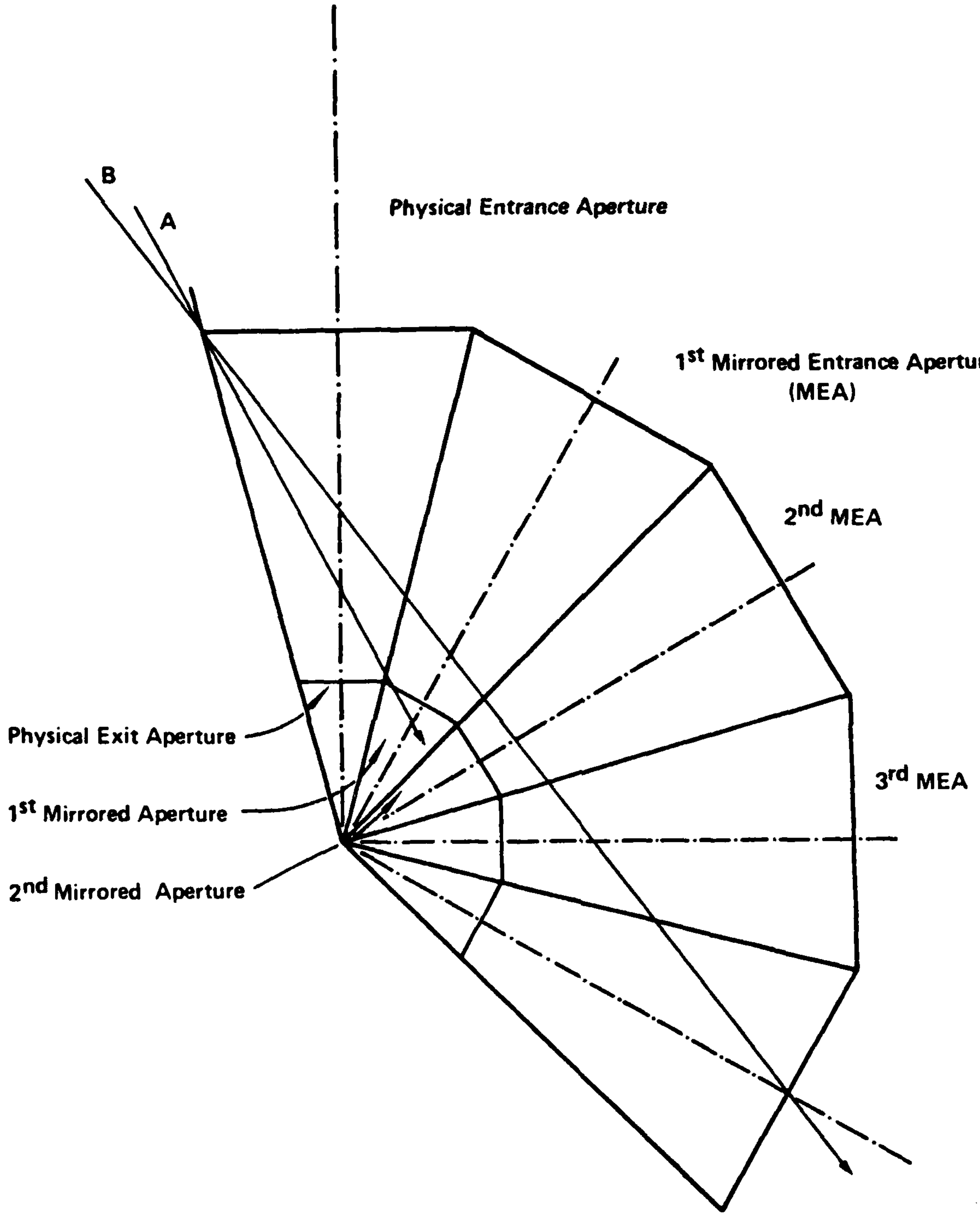


Fig. 4 Diagram for beam tracing.

temperature or the spectral composition of the light emitted.

At this point it may be pointed out that it is <u>not</u> the intent of a MAO system to produce an image for viewing by humans. It is rather the intended to collect digital data concerning a scene or object, which can be used to recognize such a scene or object. In many applications a-priori knowledge concerning the object exists, therefore only a few key data points may be required for recognition. Some of these data points need not be related to shape.

4. Field of View of the MAO System

It is desirable to adjust the Field of View (FOV) of an individual light horn in a way that the <u>central detector</u> sees a FOV which is not overlapping with the FOV of the neighboring light horns, while the surrounding detectors should see a FOV which is overlapping with at least a few neighboring FOVs. Such an arrangement will allow the detectors monitoring the overlapping FOVs to compare notes which can be exploited for motion detection or can be used in the form of a coincidence circuitry to detect pulsed phenomena.

To accomplish this the detectors have to be placed in certain strategic locations. In the insect eye six detectors form a ring around a central detector. In a focal plane array one could assign certain detectors as central detectors and others as peripheral detectors. In the case of fiber shaped detectors, the end detector would serve as the central detector, while the ring shaped detectors would collect the peripheral information.

The light horn lends itself naturally to such a bifocation since it has - in contrast to a lens - a limited acceptance angle. Rays intercepting with a too large angle are reflected out of the light horn. The maximum acceptance angle can be found using a diagram as shown in Figure 4. The left most light horn is a physical one while the others are mirror images of the physical one. The effect is that a beam reflected from the wall of the physical light horn can be drawn as a straight line through the wall. On the other side of the wall it will emerge under the correct angle as if it were reflected in the 1st mirrored light horn. This can be continued with the neighboring light horns until the ray emerges either through an entrance or exit aperture. If it should emerge through an entrance aperture as ray B in Figure 4 does this means the beam is reflected out of the light horn, and will not impinge on the detectors. In Figure 5 this procedure is generalized for light horns of any cone angle (2α). The maximum opening angle for light horns operating on regular reflection is $\gamma = 2(\beta + \alpha)$. As can be seen in Figure 5,

the optical element size were made orders of magnitudes larger than the detector size, the MAO system would degenerate into a multitude of SLE systems and would not have certain advantages the MAO system has. Since the size of the optical element is comparable with the detector size and since the detector size limits the resolving power, the overall size of the system is necessarily small.

2. Data Processing

It is no use collecting millions of pixels if the available data processing equipment cannot handle such a mass of information. The human eye has 10^8 receptors. The collected information is somewhat preprocessed since the optical nerve has only 10^6 fibers. It is safe to say that none of the existing computing machinery can rival the human brain or even the brain of lower forms of mammalian life. Therefore the number of collected pixels should be limited to conform to the capabilities to the avaliable data processing equipment. The limitations can be achieved electronically by sorting out useless information or it can be achieved optically by not collecting the useless information in the first place. If the latter is desired, averaging the intensity over a small region by optical means seems to be a reasonable approach. The light horn does this quite well. A small lens creating an Airy disk equal to the size of the diameter of the detector would do this too, however the FOV of this lens would have to be selected in a way that the projection of the Airy disk into space would fill the entire individual lens FOV. Since the wavelength of the light used determines the smallest diameter of the lens (it should be large or at least larger than the wavelength of the light) this approach is not very feasible, at least not in the IR. For this reason the use of the light horns in combination with field lenses seems to be more advantageous.

3. Resolving Power

Analyzing the resolving power of any size lens used in a SLE system will always show that SLE is superior to a MAO system. The very nature of MAO limits resolving power. However it should be kept in mind that the resolving power is only one of the qualities of an optical system. Resolving power is important for determining the shape of an object. The location of the object can be obtained without determining its shape, therefore resolving power does not necessarily limit the accuracy of determining the location of an object. There are also properties other than shape, which can be used to recognize an object e.g. its

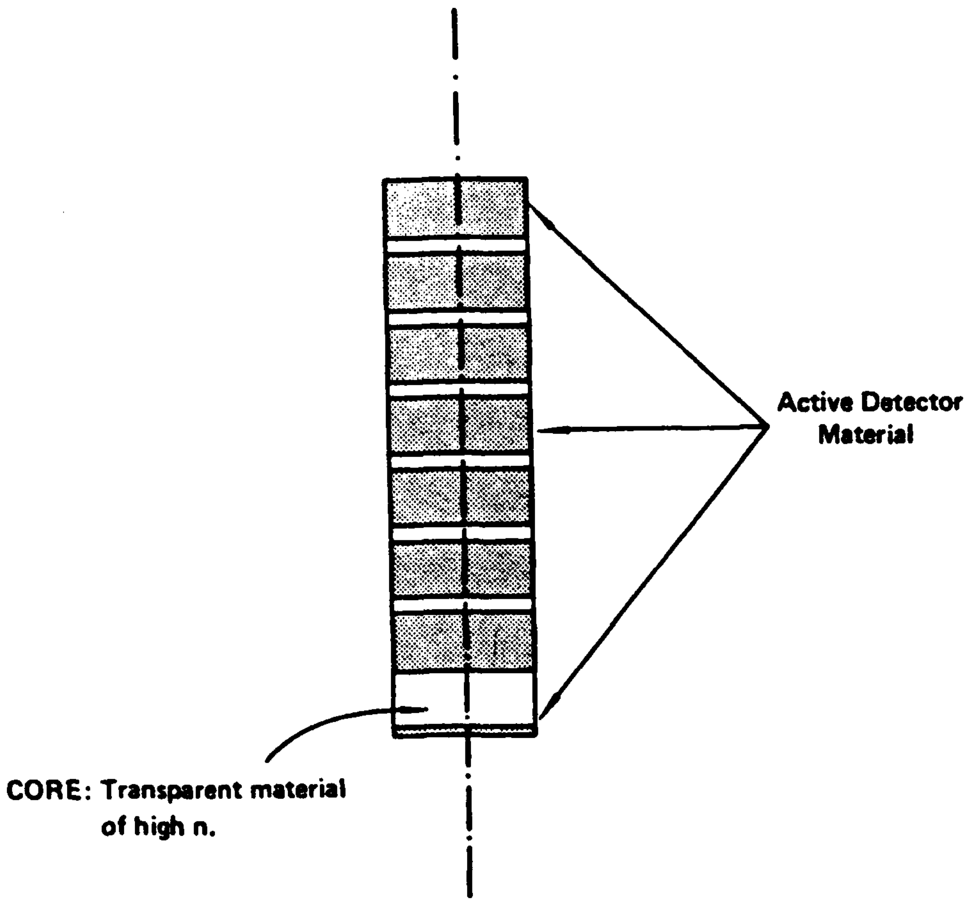


Fig. 3 Fiber shaped detector

Although each light horn is supposed to form only one pixel, the disk produced on the fibershaped detector will have some structure, depending on the fact that the light source viewed is a point light source or an extended light source. In addition, a point light source will produce a different structure on the disk depending on the location of the point light source, within the FOV.

In order to analyze the fine structure of the disk, the fiber shaped detector is configured as shown in Figure 3. The core of the detector is transparent. An oblique light ray will travel inside this core and will undergo total reflection on the wall of the core until the angle of reflection is smaller than the critical angle. At this point the ray will leave the core and will be absorbed in one of the rings of active material.

IV. PERFORMANCE OF MAO

Obviously there will be certain applications where MAO should not be used. Basically if a scanning TV camera can do the job MAO should not be considered to replace it.

As can be surmised from the previous sections MAO will be advantageous if:

1. Physical size of the system has to be small and the FOV has to be large.
2. Available data processing capability is limited.
3. Resolving power is not a prime concern for recognition of the viewed object.

These three conditions will now be discussed.

1. Physical Size

Most animals equipped with facet eyes are small, which is an indication for the validity of the above condition. The decoupling of eye diameter and focal length with respect to the achieveable f-number allows the system to be small in depth, so that the facet eye resembles a piece of skin rather than a voluminous eyeball. The skin can be bent over a sphere creating a large FOV, while in case of SLE the spherical surface is required for image formation. Since MAO is non-image forming, focussing of the MAO-eye is not required, which allows the animal to see at very close distances, while a SLE can only see objects more than one focal length away. As far as artificial systems are concerned, one would choose the smallest detectors available, since the detector size is one of the limitations for resolving power. The optical element (e.g. lighthorn matrix) serving an individual detector should be kept in size comparable to the detector size. If

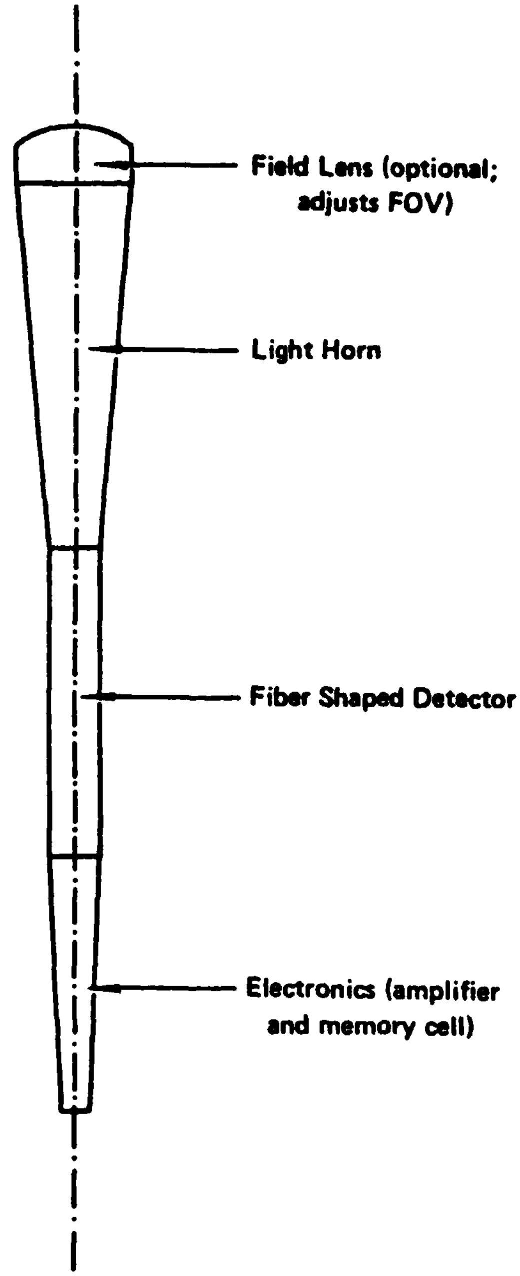


Fig. 2 One element of multiaperture system

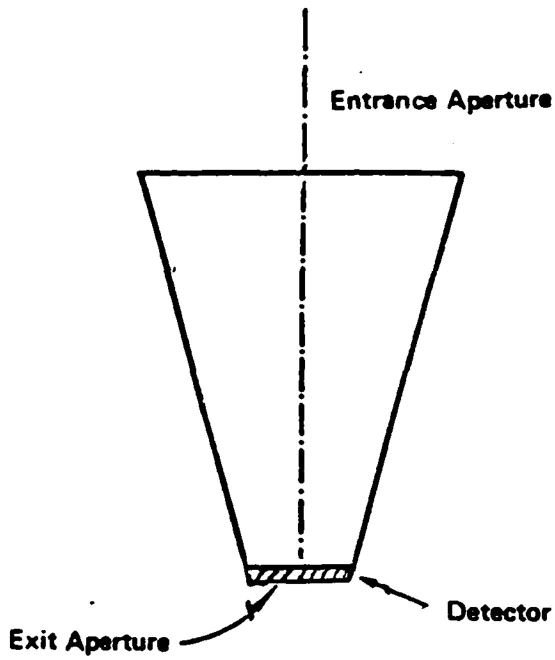


Fig. 1 Light Horn

a scrambled one). However in the beginning we defined an image as the unambiguous relationship between one object point and one image point. However, as pointed out above, in the case of MAO one object point may form many detector excitations on different locations. In summary, the difference between MAO and SLE are:

	SLE	MAO
Information Transfer:	Point-Point (Image)	Point-Matrix (Point spread sheet)
Field of View:	Focal length	Angle between eyelets
Physical Size:	Volume (Focal length and Lens Diameter)	Surface (Curvature determined by required FOV)

III. TYPICAL MAO CONFIGURATION

The statement made above may become clearer if explained by way of an example. We select a configuration, which may be typical for a MAO system. There are several criteria which help with the selection of such a system. First, since the system is non-imaging, a non-imaging optical element should be used. The light horn (Figure 1) is such an element. The entire content of the field of view of an individual light horn would result in one pixel, if only one detector (of the size of the aperture) were mounted at the exit aperture as indicated in Figure 1. As it will be shown later, indeed more than one detector is used and a fine structure of one pixel is obtained, but it is still one pixel per light horn, corresponding to the entire content of the FOV. For good resolution, the FOV of the individual eyelet is kept small, which in turn will require a large number of eyelets for a given overall FOV (the common housefly has 20,000). Therefore here the paradox exists that for MAO the resolving power becomes better if the eyelet (or lighthorn) diameter is reduced, while for SLE the resolving power becomes better if the lens diameter is increased.

An individual eyelet of a MAO system may be configured as shown in Figure 2. The lighthorn is preceded by a field lens which is used to tailor the field of view. The lighthorn illuminates the fiber shaped detector. The signal of this detector is processed by the underlying electronics and stored in a memory cell, which is connected to neighboring memory cells to form a computer core.

PREFACE

Since multiaperture optics (MAO) is a new field, this primer attempts to convey the very basic foundations of this field of optics. It is attempted to describe in concise language those aspects of MAO on which we (the group around R.T. Schneider) consider and have agreed that these are indeed established facts. This primer is intended as a first introduction for the newcomers in the field.

I. WHAT IS MAO

Most optical instruments are patterned after the human eye. MAO-instruments are patterned after the insect eye. It is presumed that the MAO eye performs a different function than the single lens eye (SLE), and that the performance of MAO is not inferior to the single lens eye in certain albeit not all aspects. The latter statement is verified by behavioral research on insects.

II. WHAT ARE THE DIFFERENCES BETWEEN MAO AND SLE

The design criteria for SLE can be summerized as follows. The single lens forms an image on the retina (or detector plane if it is a camera). An image is the two dimensial representation of the three dimensional reality in a way that each object point is represented on the image by an image point. The wave nature of light dictates that the image point cannot be a mathematical point but a disk surrounded by concentric rings, constituting the diffraction pattern of an object point. The disk is usually called an Airy disk. It contains the majority of the energy, therefore the concentric rings do not play a dominant part in the formation of the image. The consequence is that the resolving power of the lens is determined by the diameter of the Airy disk

$$A_d = 2.44\lambda(f\#)$$

while the angular resolution is given by the angle subtended by this disk

$$\alpha = 2.44\frac{\lambda}{D}$$

λ = wavelength, D = Lens Diameter, f = f-number

It follows that a design criteria for a SLE eye or camera is that the diameter of each detector has to be equal or only slightly larger than the Airy disk. If the diameter of the detectors is equal to the Airy disk, the factor limiting the

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PRIMER ON MULTIAPERTURE OPTICS

by

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index of the detector housing which should be chosen as large as possible. This guarantees that the incoming ray C is totally reflected on the detector housing wall and will therefore travel down to the end detector where it will be absorbed and produce a signal. It is desirable that a beam intersecting with the optical axis under an angle larger than δ be reflected from the light horn wall at least once and strike the detector housing wall under an angle $\lambda < \lambda_o$, thereby penetrating the detector wall housing and be detected. As can be seen from Figure 6 there is a quantum jump between the angle λ and λ_1. If the intereyelet angle is ε (it does not necessarily equal α; namely $\alpha = \varepsilon$ or $\alpha < \varepsilon$) then

$$\lambda_1 = \lambda - \varepsilon$$

If ε is made smaller than indicated in Figure 6, which certainly needs to be done for the sake of good resolving power, λ will become excessively large and λ_1 will probably still be too large compared to the critical angle achieveable with common optical materials. Therefore now a condition

$$\lambda_n < \lambda$$

would have to be stated. λ_n means the angle after n reflections. The principle here is that there will be an abrupt transition from the part of the FOV which is shared with the neighboring eyelets and the part which is exclusively observed by the eyelet under consideration.

Therefore for all further analysis it suffices to specify two angles, namely

γ: Total FOV, a part of which overlaps with the neighbors; (TFOV)

δ: Exclusive FOV, no overlap with neighbors (EFOV)

The angular resolution of one eyelet would be δ in contrast to $\alpha_r = \frac{2.44\,\lambda}{D}$ for a lens.

5. Field of View Overlap

Let us assume that the TFOV for a given MAO eyelet is three times in diameter than its EFOV. Figure 7 shows this situation. The cross hatched circle is the EFOV of a center eyelet, which is surrounded by six neighbors (numbered 1 through 6 in Figure 7). The dashed circle is the TFOV of the center eyelet, while the large circles labeled 1 through 6 are the TFOV's of the surrounding neighbors.

As can be seen from Figure 7, if a point light source or a light source no larger than the EFOV of one eyelet is observed by the EFOV of the center eyelet, then all six neighbors will observe this light source with their TFOV as well.

If the observed light source is a short time phenomenon, then the

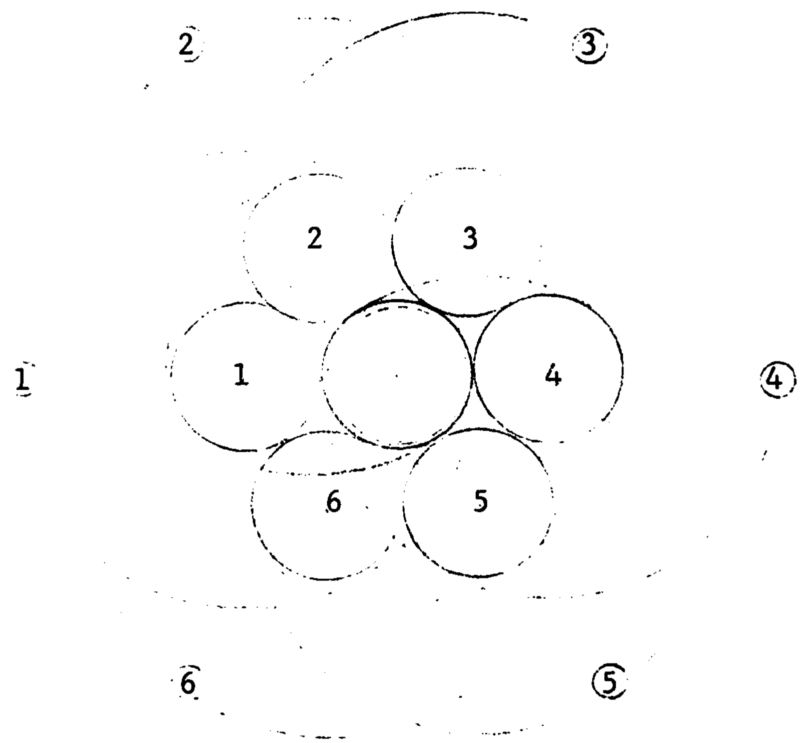


Figure 7 TFOV 3 times EFOV

probability that the observed signal stems from a target or from noise can be computed by the following reasoning. Let us say there were only one detector which observes the light flash and the signal to noise ratio is 10:1. The maximum intensity which possibly could be observed is 10 counts from a target and 1 count from noise or 11 counts. If only one count is observed than the probability that the observed count stems from noise is $p_1 = 1/11 = 0.09$. If 3 detectors see one count each at the same time, then the probability that the observed phenomenon is noise is $p = p_1 \cdot p_2 \cdot p_3$ or $1/11^3$ or $p = 7.5 \times 10^{-4}$. For six detectors it would be $p = 5.6 \times 10^{-7}$.

Table 1 shows these probabilities for an overlap of 1, 3, and 6 as a function of various S/N ratios. As can be seen this is a very powerful method to identify short light flashes, e.g. even if the S/N ratio is only 2:1, if all six neighbors record the light flash (in their TFOV), which the center eyelet sees in its EFOV, then it is virtually sure that the observed light flash is not noise.

TABLE 1

S/N	1 Detector	3 Detectors	6 Detectors
10:1	0.09	7.3×10^{-4}	5.3×10^{-7}
5:1	0.17	4.9×10^{-3}	2.4×10^{-5}
2:1	0.34	3.9×10^{-2}	1.5×10^{-3}
1:1	0.50	0.25	1.6×10^{-2}
1:2	0.66	0.29	0.08
1:5	0.83	0.57	0.33

This feature is possible because the MAO system is staring and has a large overall FOV. A scanning SLE system would have to scan and might miss the light flash altogether, or even if it sees it accidentally it will have no means to distinguish between noise and signal if the flash is shorter than one frame rate (the probabilities in row 1 of Table 1 would have to be increased in case of a scanning SLE in order to account for the off time).

A possible application may demonstrate the usefulness of MAO with overlapping TFOV's. The described device can be used as a receiver for an optical transponder. Let us assume the friendly airplane emits short bursts of IR, in coded irregular intervalls. A recticle or scanning type SLE seeker could not lock onto such a signal. The friendly missile using MAO would detect it and conclude from the repetition rate that the signal emitting airplane is friendly.

6. Motion Detection

The identification of an object requires (even with MAO) a substantial computing effort. It is enormous for SLE. Therefore the identification work should be restricted to the most important objects. The determination if an object is important or not can logically only be made after it is identified and not before. Therefore that seems to be a vicious circle, namely to try to avoid to identify unimportant objects, while this can only be done by identifying them first.

Therefore in most cases, the assumption is made that if an object moves it is important. For an animal any moving object may be a threat and needs identification. For an airplane a fast approaching object certainly should be considered a threat. We ourselves "see" things in our peripheral vision only after they start moving. For this reason a motion detector is required. The overlap in the TFOV's can obviously be used for that. To obtain the shape of an object, intensity values are usually required, to decide if pixel x is illuminated or not. A mere intensity ratio between the intensity in pixel x and its neighbor, would not suffice. In case of motion detection however this is sufficient, which is the reason why it is easier to detect motion then the object itself. Therefore if in Figure 8 lets assume an object point is centered on the cross hatched eyelet, and the EFOV is identical to the cross hatched circle. Therefore the point is seen by the EFOV of one eyelet (the cross hatched one) and 6 TFOV as indicated in Figure 7. Now lets move the point in Figure 8 to the right neighbor, namely EFOV number 2. TFOV 5 now no longer sees the point while the intensity in TFOV 6 and 4 is reduced drastically. On the other hand TFOV 4' and TFOV 6' gain intensity.

As can be seen any change in the intensity ratio of two neighboring EFOV's requires a confirming change in the intensity ratio for certain TFOV's, the magnitude of the change need to fall into a certain pattern, according to the above discussion. Only if these conditions are fullfilled will the system report a motion otherwise the system will conclude that the observed fluctuation is due to noise. As shown in Table I an overlap of FOV's in a way that six detectors always see the object will create almost certainly even for S/N ratios as low as 2:1. However if even larger overlaps were chosen movement could be detected for S/N ratios < 1.

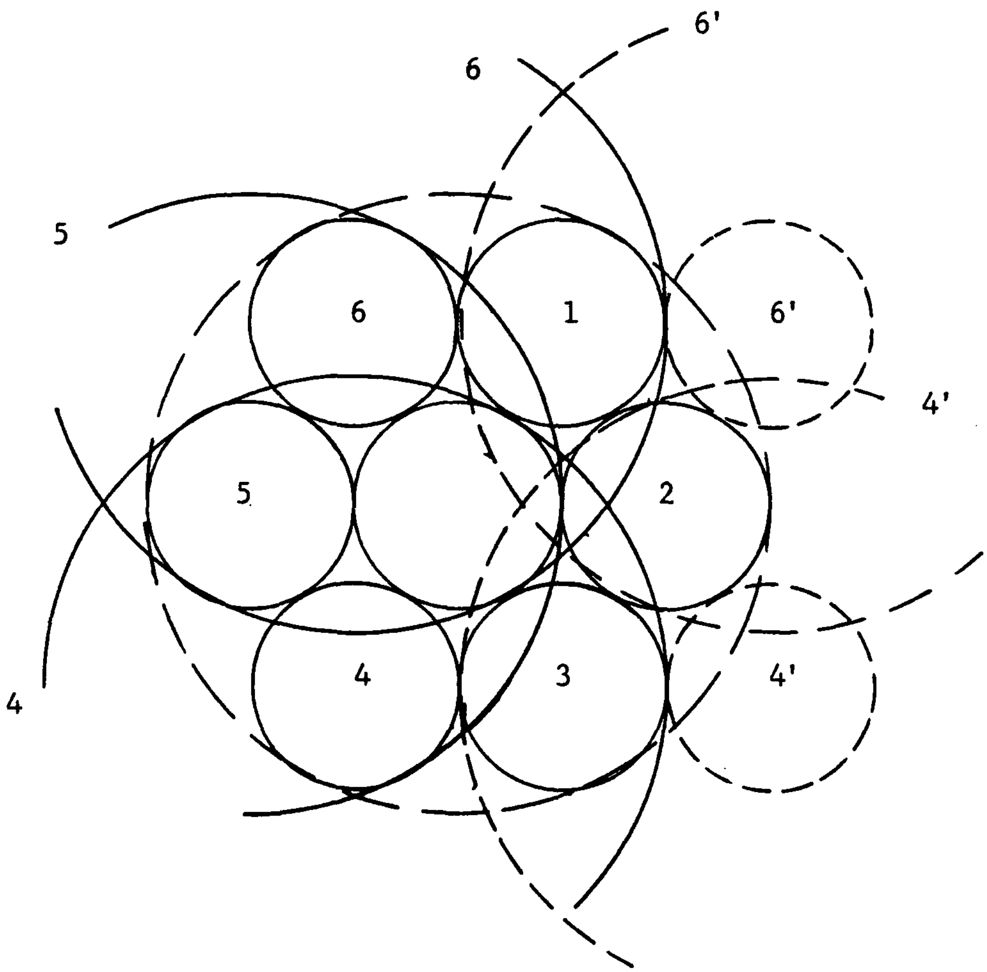


Figure 8 Intensity Distribution for Motion Detection.

V. COMPARISON OF MAO TO NATURE

Since multiaperture optical system exist in nature in the form of insect eyes, it is advantageous to compare any proposed design to these natural systems. There are basically two types of insect eyes, the apposition eye and the superposition eye.

1. Apposition Eye

In general it is automatically assumed by the workers in the field that the insect eye produces an image which is handed over to the brain as such. In contrast to this we believe that the eye is a digital data gathering device, which recognizes objects in the eye and only transmits the results of the recognition to the brain. Nevertheless the mosaic theory of insect eyes states that each eyelet (ommatidium) contributes one point to the image the insect conceives. Depending on the species, there can be up to 20,000 ommatidia in an eye. In this case, the image would be made up of 20,000 pixels, which would make an image of only moderate quality. However, there are indications obtained through behavioral research that the insect, in deed, sees quite well. The suspicion therefore is that one ommatidium does more than collect only one point of the image.

Figure 9 is a simplified diagram of the structure of an apposition eye. The main optical elements consist of two lenses (the corneal lens and the crystalline cone) and a bundle of 7 to 8 detectors (the rhabdom). We like to suggest that the cone is a light horn, while the corneal lens is a field lens. And indeed, in Reference 1 it is claimed that the crystalline cone is almost identical to the ideal concentrator (light horn). However this assumes that the refractive index is a uniform $n = 1.54$, which is actually not the case for most eyes. Rather, the index is changing in the radial direction. However this should not modify the function of the light horn too much.

The rhabdom, which is a long hose-like structure, contains 7-8 individual detectors (the rhabdomeres). They are either separated or fused together as indicated in Figure 10. Most apposition eyes have fused rhabdoms. In this case, indications are that each rhabdomere has a different color sensitivity and/or serves as a color filter for its neighbors.

A rhabdomere is made up of layers of small tubes, typically 1μm in diameter, which are alternatingly oriented, 90 degrees to each other (see Figure 11). These tubes are called microvilli; they are the organs which convert light energy into electrical energy. The light is kept inside the rhabdom by total reflection on

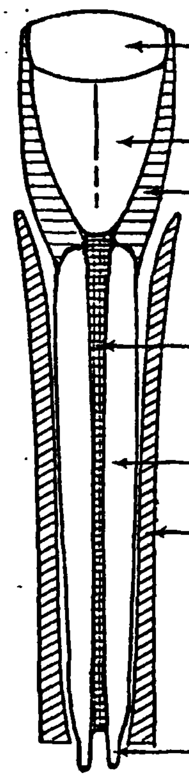
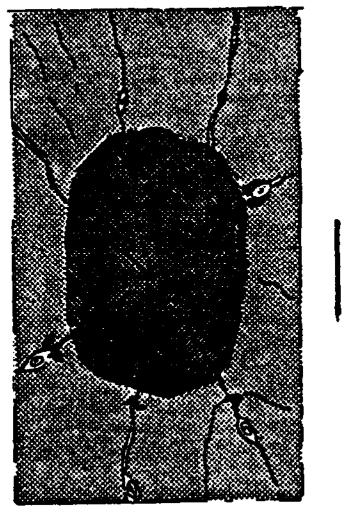
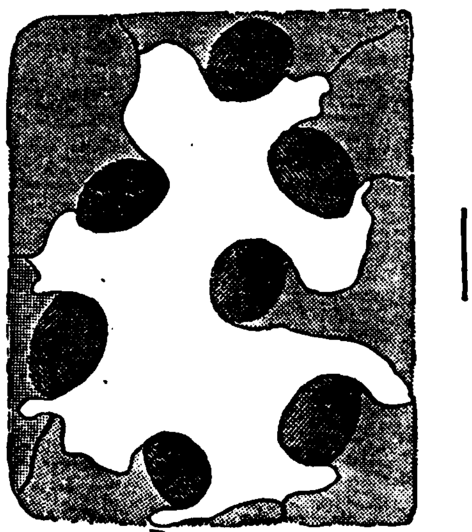


Figure 9 The Apposition Eye



Fused
Rhabdom



Separated
Rhabdom

Figure 10 Rhabdoms

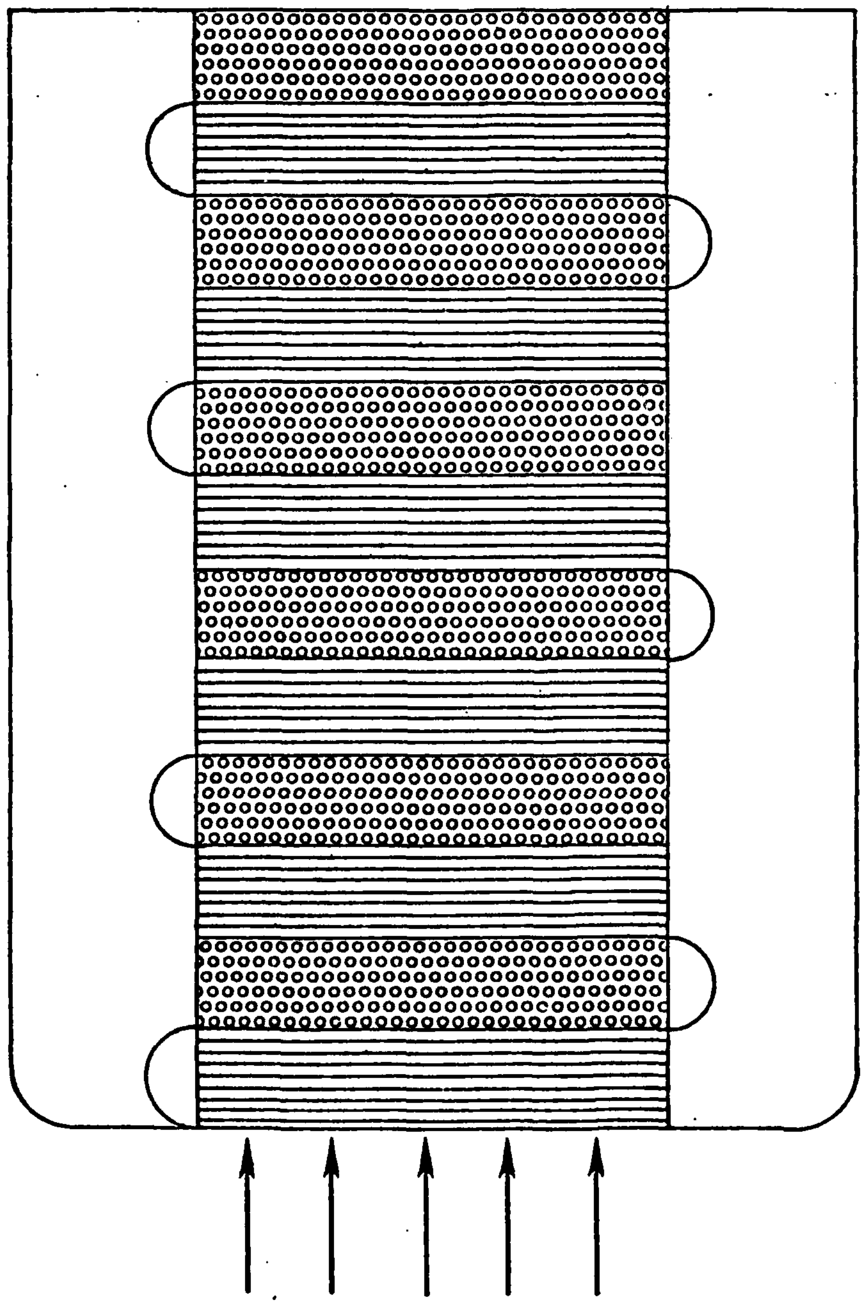


Figure 11 Structure of Rhabdom, Showing Microvilli

the internal walls of this hose-like structure.

Each ommatidium is surrounded by pigment cells. This pigment serves as optical insulation between neighboring ommatidia.

2. The Superposition Eye

This type of eye, as can be seen in Figure 12, is similar to the apposition eye. The main difference is a piece of fiber optics (the cytoplasmic filament) which is inserted between the crystalline cone and the rhabdom. At low light levels there is no optical insulation between the individual cytoplasmic filaments. However, if high light levels are present a pigment layer is moved between each filament as indicated in Figure 12.

For the case when there is no pigment between the filaments, the theory states that the image which is formed by each lens spreads out over more than one rhabdom, in fact, a large number of rhabdoms. This is, of course true for each lens and, therefore, many images are superimposed. If properly aligned, they should form one superposition image.

Not all entomologists subscribe to this theory, therefore the superposition eye is sometimes also called "clear zone eye," referring to the clear space between the crystalline cone and the rhabdom.

The fact that the superposition eye turns into an apposition eye at high light levels makes one wonder about the validity of the theory of the superposition image. It should be noted that not only the pigment needs to be withdrawn, but also the refractive index of the filament has to be made equal to the index of the surrounding liquid to allow formation of a superposition image.

Based on what was said earlier in this section, we like to venture the opinion that the cytoplasmic filament is a device which limits the FOV of the individual eyelet. The superpositon eye is usually associated with a separated rhabdom (detector array) as shown in Figure 10 (lower half). The detectors form a ring containing six detectors which surround a central detector number 7 (or to be precise 7 and 8 which are fused together). We would like to assume that the center detector sees only the non-overlapping part of the FOV, while the ring of six detectors detect the overlapping parts of the FOV as described above. If the filament serves as a waveguide in both cases, high light level and low light level, the introduction of pigment around the cytoplasmic filament would only change (by frustrated total reflection) the intensity carried in the waveguide but not change the method of data evaluation.

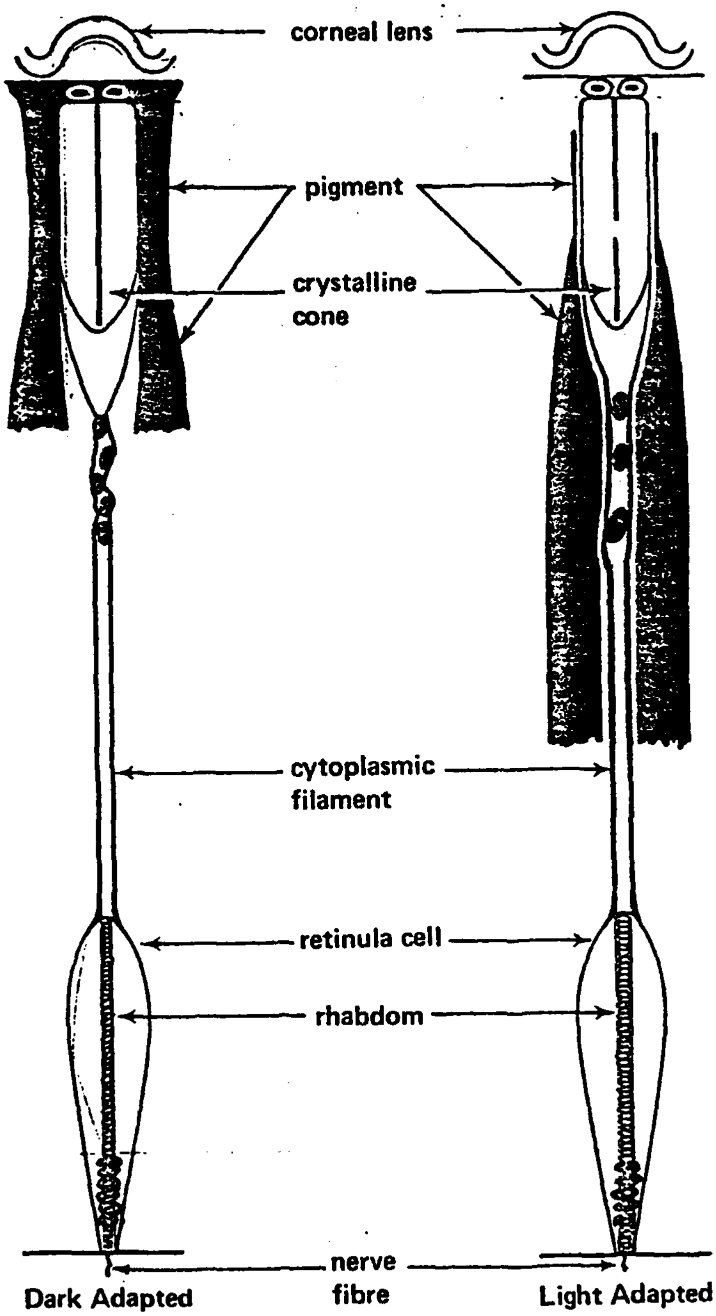


Figure 12 The Superposition Eye

There are three layers of nerve nets underlaying the eye structure (as mpared to only two in case of the human eye) and relatively few nerves connect to e brain. We suggest that the pattern recognition is performed in these nerve ts, very similar to what we have proposed for MAO systems, and only the result of e pattern recognition is forwarded to the brain.

There is experimental evidence that both eyes communicate with each other. g. if only one ommatidium in one eye is illuminated, the brain checks if the rresponding ommatidium in the other eye is also illuminated. It can do this spite the fact that only a few nerves are connected to the brain, meaning that t every ommatidium has its own connection to the brain. In order to select a rtain ommatidium in the other eye the incomming signal must be coded in respect the position of the illumintated ommatidium. This is a strong indication that bstantial processing performed in the eye itself.

For this reason we suspect that the insect eye is not a camera delivering an age to the brain, but a pattern recognition device delivering a signal to the ain, which announces the kind and location of an identified object. The same al we see for the MAO system. It is not to be used as a TV camera, providing an age for a human observer, but as a device which recognizes an object and nounces its location.

. DIFFERENT DEGREES OF FOV OVERLAP

If a given aperture is divided into a multitude of smaller apertures the herence of the incoming light wave is destroyed, which necessarily must lead to duced resolving power. This is always an argument against MAO, and is indeed a sadvantage. There have to be advantages for MAO which outweigh this sadvantage. Obviously applications requiring high resolving powers should not considered for MAO.

The limited resolving power of MAO is determined by the degree of overlap of e FOV's between neighboring eyelets. Logically there are three cases of erlap possible. They are:

a. Total overlap

b. Partial overlap

c. No overlap at all.

By total overlap we mean that each eyelet sees exactly the same as the ighboring one. Compared to a SLE camera of the same aperture such a total

rlapping MAO camera would intercept the same photon flux and would distribute, image of one object point over n detectors if there were n eyelets in the MAO era. Of course the SLE camera uses only one detector for the one image point it ates from an object point. The consequence is that the signal to noise ratio t be inferior for the MAO camera by a factor of n compared to the SLE camera. ever it turns out that this factor can be recovered if the application required arge FOV, so that the SLE camera need to be scanned, while the MAO camera can re. This situation is explored in more detail in the attached Appendix I. ever we consider such a situation not a true MAO camera. It is really a titiude of SLE cameras, albeit such an arrangement may be very useful for some lications. Also a closer examination of the situation shows that even for atively small SLE lens diameters the Airy disk becomes so small that literally lions of detectors are required to provide voidless coverage of the image. If data reduction system cannot digest this mass of data the above comparison to is no longer valid.

Now consider the case of no overlap at all (case 3). Here again the olving power is poor. It increases with the number of eyelets (n). Of course a given overall aperture the diameter of the individual eyelet decreases with Again such a MAO arrangement offers staring as opposed to scanning as a SLE iera must do. Therefore it may see objects of a transient nature, which the SLE era might miss. Therefore a comparison between the two systems is really not sible. If there is a need to rely on detection of transient objects scattered r a large FOV the SLE camera is not really an option and a MAO camera need to be d irregardless of poor resolving power and low SNR.

This leads us to the case of partial overlap (case 2) where the TFOV can be d to verify the existence of the transient object by coincidence. However such eparation into TFOV and EFOV can only be accomplished by a non-imaging system, e a light horn.

From the above discussion we see that the MAO system can be adapted to the sting requirement not only by the selection of n but also the selection of the ree of overlap of the FOV's of the individual eyelets. The latter one does not essarily need to be constant over the entire MAO system.

To illustrate the above statements let us assume a special application for ch MAO is well suited. Assume the requirement is a camera for a blind person. s camera would be worn attached, let us say to the chest, and it would be able to ognize objects and call these out, using an earphone, naming what they are and

re they are. For the latter one to make sense the camera would have to be rly rigidly attached to the blind persons chest, so that a call out warning of object approaching from the right actually means something. When analyzing se requirements it can be seen that a 180 degree FOV is mandatory. One lividual SLE camera could not accomplish this. Using a MAO camera the resolving er will be fairly low, therefore only crude outlines can be detected. If there a large obstruction in the way of where the blind person is going it certainly l be detected, albeit without the distinction of whether it is a brick wall or t a wooden fence. Also larger objects, like cars coming from the side will be ected by the described motion detector, without being recognized as such. The umption that anything which moves poses a threat will have to be made. refore the overlap of the individual FOV's will be chosen larger at the iphery of the eye then in the center.

If a SLE camera were to be used for the same purpose the blind person would e to scan this camera to detect danger, pretty much the same way we do with our ing eyes. However our eyes get attracted to such a danger also by a built-in tion detector in our peripheral vision. Therefore a TV camera could not meet is particular requirement. Also if the camera were to be scanned the formation where to the optical axis is pointed at a particular point in time uld somehow have to be provided by some outside means while this information is herently known in case of the MAO. The resolution of the TV camera would of urse be excellent. However the computer to sort out this mass of data would have be so big that the blind person could not carry it with him. Therefore falling ck to a reasonably sized pattern recognition system, one would have to resort to ly trying to recognize simple shapes and one would be back to the performance ich MAO also offers, but without having the advantages of MAO.

I. APPLICATIONS

1. General Remarks

As pointed out in the previous discussions there is a basic difference in tical principles between a single lens eye and a multiaperture eye. This fference is that the single lens eye is image forming which is an analog enomenon, while the multiaperture eye, disects the total field of view into a rge number of individual fields of view. The contents of each individual FOV is alyzed for various characteristics such as motion, color, etc. whereby pixel

formation is only one of the characteristics investigated. The act of disecting the total FOV is a quantization, which requires digital presentation of the addresses of each individual FOV. The contents of the individual FOVs are again disected into different zones, which again is a quantization where the fact of a signal is present or not, or if it changes its value or not, is more important than the absolute value of the signal. Again such a situation can be handled well by digital techniques. Therefore basically the multiaperture eye is a digital data collecting device, while the single lens eye is an (analog) imaging device.

If a device does nothing but imaging, resolving power is the most important criterion to judge its performance. Applications where resolving power is the foremost concern, should therefore be reserved for the single lens eye. However if for example a motion in the peripheral vision has to be detected because every object coming from the side is considered a threat, an image forming system would first have to acquire the shape of the object and than decide in the next frame if this shape has moved in respect to all the other shapes which are also albeit unwillingly acquired. This is done despite the fact that the shape is of no interest, and therefore the procedure is necessarily very inefficient. A multiaperture system of course would only have to check if in a certain group of eyelets, intensities move in a concerted manor amongst the different zones, of each eyelet. (For more details see "motion detector" section found earlier in this report.)

Based on the above discussions one can see that there are a few ground rules for choosing applications for multiaperture optics, which should be observed. All applications which can satisfactorily be done with a TV camera should not be considered for multiaperture optics. Also appliations which require minute details of the shape of an object should be left to the single lens eye. On the other hand there are applications which can only be handled by MAO. These are all applications requiring a wide FOV and applications concerned with the observation of transient phenomena. To clarify the last statement consider both a single lens camera and a MAO camera receive a light flash. In order to distinguish if this was indeed a signal or a noise spike the MAO camera can seek verification by checking for coincidences with neighboring eyelets which should have seen this flash too if it were a signal. The single lens camera has no such option for verification.

Before discussing individual examples of applications for MAO we should outline at least the conceptual design of a MAO eye. Based on the pecularities of MAO optics nature developed MAO eyes only for a certain class of animals, namely

invertebrae. These invertebrae have two things in common, they are small and due to their exoskeleton they have a hard time moving their heads. Translated into optics terms this means a wide field of view, no scanning, and small individual entrance apertures (typically 100 x wavelength which compares to 1000 x wavelength as the typical lower limit for single lens optics).

It is probably safe to say that after many million years of evolution the optimum configurations have been achieved. Therefore a man made MAO device will have to resemble an insect eye to some degree. Obviously one wants to utilize the wide FOV, which eliminates the need for scanning and due to the requirement for a reasonable resolving power the total FOV has to be devided in a large number of individual FOVs which leads to small entrance apertures. (Large entrance apertures could be used of course but then the need for a multitude of them becomes questionable.)

Considering all this one can expect the MAO eye to be the size of a postage stamp with individual apertures of 100µm for visible light. The smallness of the eye would make it prohibitively expensive unless microchip technology is used.

Figure 13 shows the conceptural design of a MAO camera. It consists of a MAO mask featuring light horns and possibly field lenses. The MAO mask conforms to a radius of curvature although the bottom part of it is ground flat. This mask was developed under the present effort and is now available. Underneath the MAO mask is a spacer which provides a space between the MAO mask and the memory board. The memory board contains detectors on the surface. There are seven detectors for each light horn as pointed out earlier (Figure 7) in this report. The memory board also contains one memory cell for each detector. The memory cell is fed directly (parallel) by its respective detector. Underneath the memory board is the hard wire board which is exchangeable. The hard wire board contains the instructions how to read and manipulate the contents of the memory in hard wired form.

2. <u>Typical Applications</u>

General Camera

A multiaperture camera as described above could be used as an all purpose eye for a vehicle (cruise missile, ships look out, robot, land mine detector, tail guard, etc.). Since a hard wire board, which can contain recognition codes, is an integral part of the eye it can recognize objects and give steering commands to a vehicle.

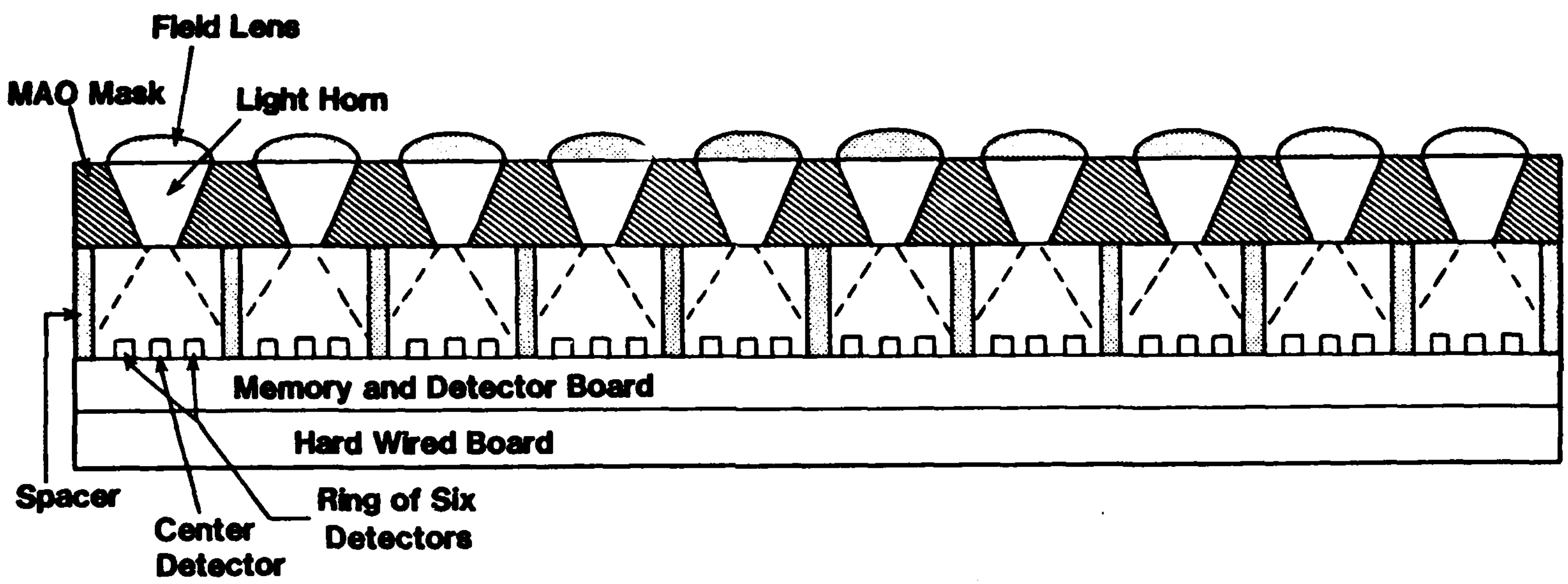


Figure 13 Multiaperture Optics (MAO) Device

Motion Detector

A MAO eye in the shape of a hemisphere can be mounted on the ceiling of a room to be safeguarded. The eye will be programmed to check for motion rather than recognition of shapes. This is probably the most simple application for MAO. As can be gathered from the discussions earlier in this report the motion detector is very powerful since it can work with coincidences. The algorithms for it are much simpler than the ones for recognition schemes. (This would be a very simple device which could be mounted on ships to look out for moving objects.)

Tracking and Measuring

Unpredictable phenomena like meteor traces or lightning paths can be followed by a hemispherical eye, similar to the motion detector mentioned above. Only this time the eye is programmed for recognition of simple shapes. Such an instrument could be used to do statistics on lightning or meteor showers. It could also be used for solar research although the sun travels slower. In this case the size of an individual FOV will be chosen so that it will just be filled by the image of the sun. The rest of the eyelet will then be used to collect data concerning the scattered radiation, cloud coverage, etc.

Robotics

One problem encountered with robotics, which is new compared to conventional automation, is that the robot can move its arms freely and it can smash into objects or people. Therefore a visual system to prevent such mishaps would be very desirable. It is easily seen that a TV camera mounted on a central location (head) of the robot would require a large amount of computing power to recognize objects and correlate them in respect to the position of the arms. Obviously it is impractical to mount a TV camera on the moving arm. However a postage stamp sized MAO eye can be easily mounted on the "hand." It will not be bothered by acceleration and deceleration. With a pair of these MAO eyes mounted triangulation can be performed which would tell the system how far away the interfering object is. Obviously only the fact that an interfering object is present needs to be detected, not what it is. Therefore a simple recognition scheme which is of course handled in the eye itself, will suffice. Also since MAO is non-image forming, focussing of the eye is not required, which is very important for this particular application.

A hand mounted eye could also be used to find and identify a certain part

which the robot needs to install. Here of course a more sophisticated recognition scheme will be necessary. However since a-priori knowledge exists, how the part looks like, the peculiarities of MAO can be used, so that the eye would only recognize the desired part while all other objects will be classified as interfering objects and will only become a concern if they are close enough to interfere with the movement of the arm.

Parts Inspection

As can be sensed by reviewing the applications discussed, so far MAO is best applied to situations where low resolving power and simple recognition schemes are adequate. A very good example is parts inspection. For example, if one wanted to inspect beverage bottles on the production line for cleanliness, absence of cracks, and absence of foreign mass, the recognition scheme seems to be so complicated (and therefore expensive to develop) that still in many instances a human inspector is used. MAO however fills these requirements with ease. Each individual FOV inspects a certain volume element in the bottle. It is easy to define which ones have to be empty and which ones do not. If there is a foreign object in the bottle, only this fact has to be detected, rather than the shape of the object itself. Therefore a reduction in intensity in one or more of the FOVs which should show empty (high intensity) is already sufficient to reject the part. A smudge on the surface of the bottle can be detected with intensity ratios between neighboring eyelets. The same is true for cracks. It is also easy to adjust for different glass coloration by simple averaging over the eyelets which view the empty part of the bottle.

Gazing Sensors

Future military requirements will contain a greater necessity to detect in which direction (e.g. in respect to his helmet or in respect to the airframe) a pilot looks. For this reason the movement of his eyes has to be monitored and the center of the pupil has to be recognized. A MAO device is small enough to be mounted in the rim of the helmet and observe the pilot eyes without interfering with his vision and without adding an undue amount of weight to the helmet. It is even possible to mount the device in the lower (unused) part of the eyeglasses. The recognition scheme is very simple and can be accomplished inside the MAO device.

Blind Man's Eyes

A set of eyes which recognizes objects and points out kind and position of such objects by verbal communications would be an invaluable aid for blind people. In principle this could be accomplished by two TV cameras served by a large computer. Obviously such a system would not be very practical. However MAO devices are small enough that they could be carried by a person, recognition is done in the MAO eye already, what still needs to be added is a speech synthesizer which translates the output of the MAO device into words.

Only simple shapes would have to be recognized. For example if an object is dead ahead the shape of the object is not very important but its distance is. This distance can be obtained by triangulation. Also moving objects are of importance. Any movement has to be considered as a threat and therefore detection of movement (motion detector) could be done without recognition of the moving object. Here recognition of simple shapes goes along with low resolution and makes this a practical device for a blind person to wear. Only a few words would be required for the speech synthesizer. They could be pre-stored in a chip and called when needed.

Application to X-rays

Regular x-ray "images" are actually not images but shadowgraphs. Cat-scans are computed images. If a collimator mask is added to the MAO device it becomes a x-ray imaging device. The collimator mask consists of a multitude of small hollow lead cylinders. The diameter of these cylinders is equal the entrance pupil of the individual MAO eyelets and the axis of each cylinder coincides with the optical axis of the particular eyelet it serves. The light horns in the eyelets are filled with a scintillation material. The light generated by the x-rays is detected by the detectors mounted underneath the light horns. Such a MAO device could be built in larger sizes so that the total aperture would be larger than a pinhole in a x-ray pinhole camera.

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